2023

# Hydrologic and Hydraulic Impact Analyses of the CPC Lands

AN URBAN FLOOD MITIGATION STUDY
FOR THE COASTAL PRAIRIE CONSERVANCY

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## Executive Summary

This study investigates and quantifies the flood reduction benefits of native prairie vegetation in the Upper Cypress Creek watershed, particularly as to those lands owned or maintained by the Coastal Prairie Conservancy (CPC). For example, such vegetation both absorbs rainfall itself as well as enhances the ability of the soil to absorb rainfall, thus reducing the amount of rainfall that becomes runoff (a **retention** function). Such vegetation also slows down the movement of stormwater runoff (a **detention** function). These retention/detention functions of this vegetation provide a clear and significant benefit to flood reduction in the upper Cypress Creek watershed, as well as reducing the overflows into the Addicks watershed and reducing the flows going downstream along Cypress Creek.

This report summarizes the methodology applied in this study to quantify the current detention and retention capacity of CPC land. As a result, this report additionally provides insight on the future influence of the land in flood mitigation with prairie restoration and expansion. This information is pertinent to the investigation of alternative flood mitigation options for upper Cypress Creek in attempts to conserve and protect the current coastal prairie as well as enhance or expand such vegetation as an alternative to reservoirs and additional gray infrastructure. As such, the main findings of this study are summarized below:

- Infiltration testing performed on CPC property confirmed that prairie vegetation enhances infiltration rates of topsoil, and creates higher infiltration rates as compared to the other vegetation types tested in this study.
- These higher infiltration rates attributed to prairie vegetation were proven to reduce peak flows of stormwater runoff through hydrologic modeling performed in this study.
- The hydrologic land-conversion portion of this study concluded that expanding and restoring native tallgrass prairie would increase rainfall **retention** up to 0.2 acre-ft/acre of converted land. This was found to be largely controlled by topsoil depth, so further investigation and surveys of soil depth within the CPC property is recommended.
- Overland flow roughness associated with native tallgrass prairie, along with the current state of CPC land, provides a substantial **detention** storage effect on rainfall-runoff, even for large volume (e.g. 500-yr) storm events, of about 0.5 acre-ft/acre.
- A prairie expansion and restoration program has the potential to reduce peak flows of rainfall-runoff on average between 10-30% within upper Cypress Creek, due to the detention effects of the overland roughness of this vegetation alone.
- Hydrologic modeling in this study further demonstrated that, to fully mitigate a fully developed area, there needs to be nearly double the amount of detention storage than the minimum required by the Harris County Flood Control District (HCFCD) developmental standards (updated in 2019 to incorporate Atlas 14 rainfall volumes).
- 2D hydraulic modeling provided some initial insight into the potential depression storage potential in the Katy Prairie region, which is created through natural depressions in the topography known as prairie potholes. More analysis is needed.

## 1. Introduction

This is an investigation of the hydrologic and hydraulic functions of the Coastal Prairie Conservancy (CPC) lands in the Upper Cypress Creek Watershed on providing flood mitigation benefits to downstream areas, particularly in regard to the reduction in runoff volume overflowing into the Addicks Watershed and eventually into Addicks Reservoir (which provides flood protection to downtown Houston) (see **Figure 1**). CPC lands are located within the larger historic Katy Prairie, where native prairie vegetation and wetlands were prevalent (see **Figure 2**). This native prairie vegetation has a greater capacity to absorb water entering the underlying soil as infiltration during a rain event than other types of land covers, such as pasture or developed grassland. As such, the CPC has been conserving, preserving, and enhancing its lands in order to keep and even expand the flood mitigation benefits of this natural landscape. However, as development proceeded westward from Houston, much of this natural land cover has been converted to residential developments. Thus, one of the questions being investigated in this study is what is the infiltration rates of the various land cover types that exist in and around the CPC lands, and how would converting some of these land cover types to native prairie enhance the amount of rainfall that would be infiltrated into the underlying soils and thereby reduce the amount of runoff overflowing into the Addicks Watershed. While it has been reported that such native prairie vegetation can also increase the capacity of the underlying soils to absorb more water, this study does not address that issue (a study by AES was conducted for CPC that did discuss this issue – Apfelbaum et al. 2018). Furthermore, it is well-known that vegetative land cover can provide other flood mitigation benefits, such as providing detention-like benefits by slowing down the movement of stormwater across the surface of the land. Finally, there are natural depressions within the Katy Prairie that provide retention-type benefits by capturing and retaining rainfall-runoff as water moves across the surface of the landscape, reducing the amount of water flowing downstream. These additional benefits were also investigated during this study, to determine how much flooding is reduced due to such detention/retention benefits under different land cover conditions.

The Katy Prairie, specifically the current CPC lands, provides a wealth of ecosystem services and economic benefits to the surrounding area. The CPC land encompasses and encourages a wide variety of land use including wildlife preserves, riparian woods, wetlands, working ranches, and small-scale agriculture. The natural, undeveloped landscape slows flood waters, filters stormwater runoff, and sequesters carbon – each of which has a unique economic benefit (Apfelbaum et al. 2018). In addition, CPC land contributes to the local economy as a tourist destination for birders from around the globe (The Trust for Public Land 2018). This study focuses on the flood mitigation benefits that the CPC lands provide, due to their native prairie vegetation and wetland landscape, and the additional benefits provided by converting current land uses to native prairie vegetation.

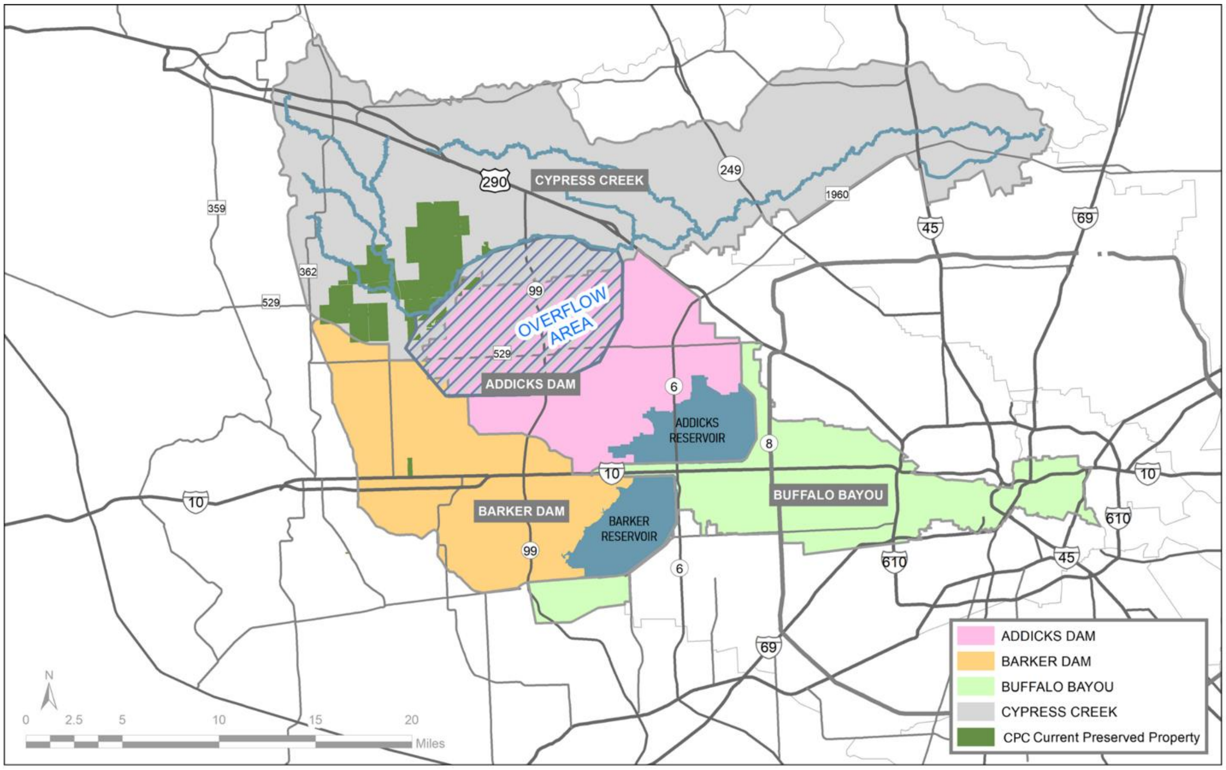


**Figure 1. Location Map for CPC Lands and Overflow Area in Upper Cypress Creek Watershed**

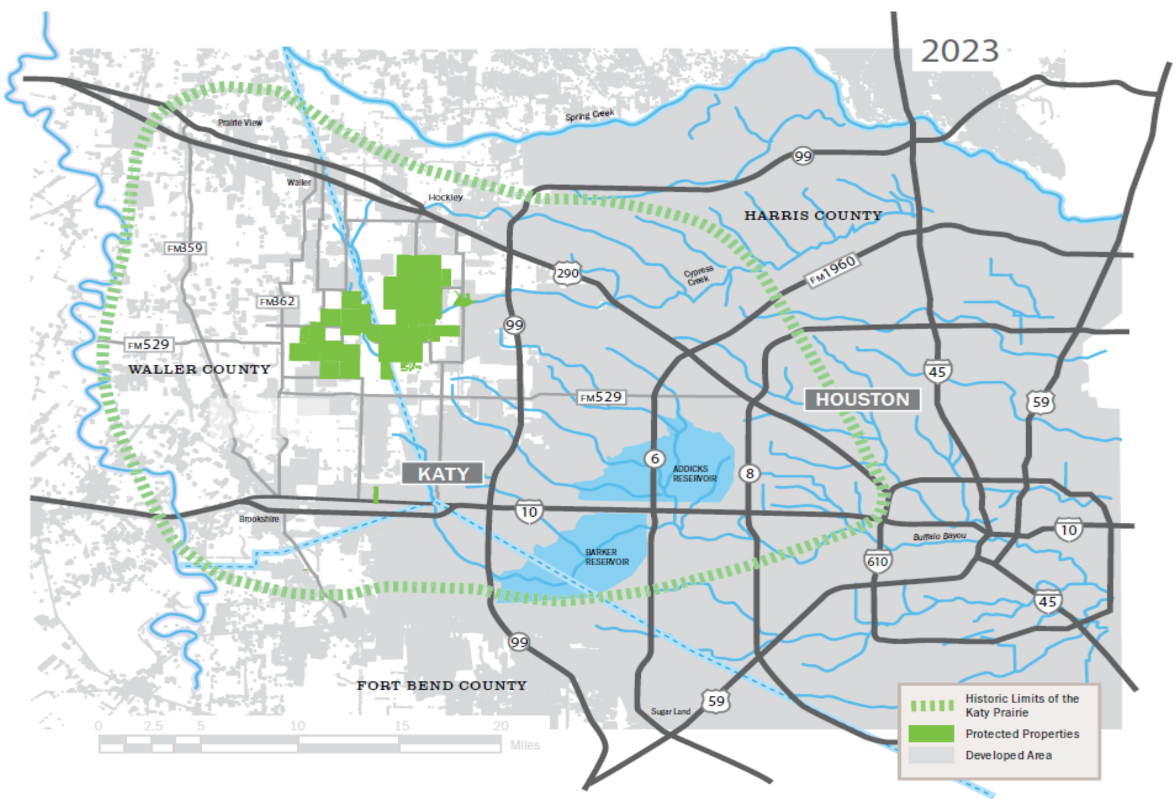


**Figure 2. Location map for CPC lands and the Historic Katy Prairie (Source: CPC)**

## 2. Scope of Work

The scope of work established with the CPC for this study consisted of the following tasks:

(1) Conduct field measurements of the infiltration rates of various land cover types in and around CPC lands to identify the hydraulic conductivity, K, value (infiltration rate in inches per hour) for different vegetative land cover types;
(2) Obtain the hydrologic model (HEC-HMS) for the Cypress Creek Watershed, and the hydraulic model (HEC-RAS) for Cypress Creek, both from the Harris County Flood Control District's M3 Library, and use these models as appropriate to simulate the runoff from the various land cover types within the watershed for various frequency storm events;
(3) Develop and utilize a hydrologic distributed model (Vflo) for the Cypress Creek Watershed, and in particular for the upper portion of this watershed where the CPC lands are located, to more accurately simulate the rainfall/runoff relationship for the various land cover types within the watershed for various frequency storm events;
(4) Use the Vflo model to simulate various scenarios of converting certain existing land cover types to native prairie vegetation and identify the reduction in runoff associated with these various scenarios;
(5) Develop and utilize an unsteady HEC-RAS 1D model of Cypress Creek, including a 2D component for the overflow area, to identify the change in overflows associated with the various scenarios of land cover conversion for various frequency storm events (this was further analyzed using a rain-on-grid HEC-RAS 2D model developed for the upper portions of Cypress Creek and Addicks watersheds;
(6) Evaluate how much inundation would result from the HCFCD's Management Plan 5 berm system, particularly on CPC lands;
(7) Prepare a report detailing the results of the various analyses conducted above, and provide an evaluation of the results and recommendations, if any, for further work.

## 3. Field Testing of Infiltration Rates

One of CPC's ecological consultants, Applied Ecological Services, Inc. (AES), identified various site locations for conducting infiltration tests in order to obtain infiltration rates (K), in inches per hour, for certain land cover types that can then be incorporated into the hydrologic modeling of the upper Cypress Creek Watershed. The different land cover types for which infiltration tests were conducted included the following: prairie, wet prairie, pasture, open space, rice and row crop.

As shown in **Figure 3**, there were fifteen (15) different sites where field tests were conducted. At each site, three separate tests at slightly different locations were conducted to measure and obtain infiltration rates for the site. The three separate tests were conducted using three infiltrometers at each site. The details of these infiltration tests can be found in **Appendix A**.

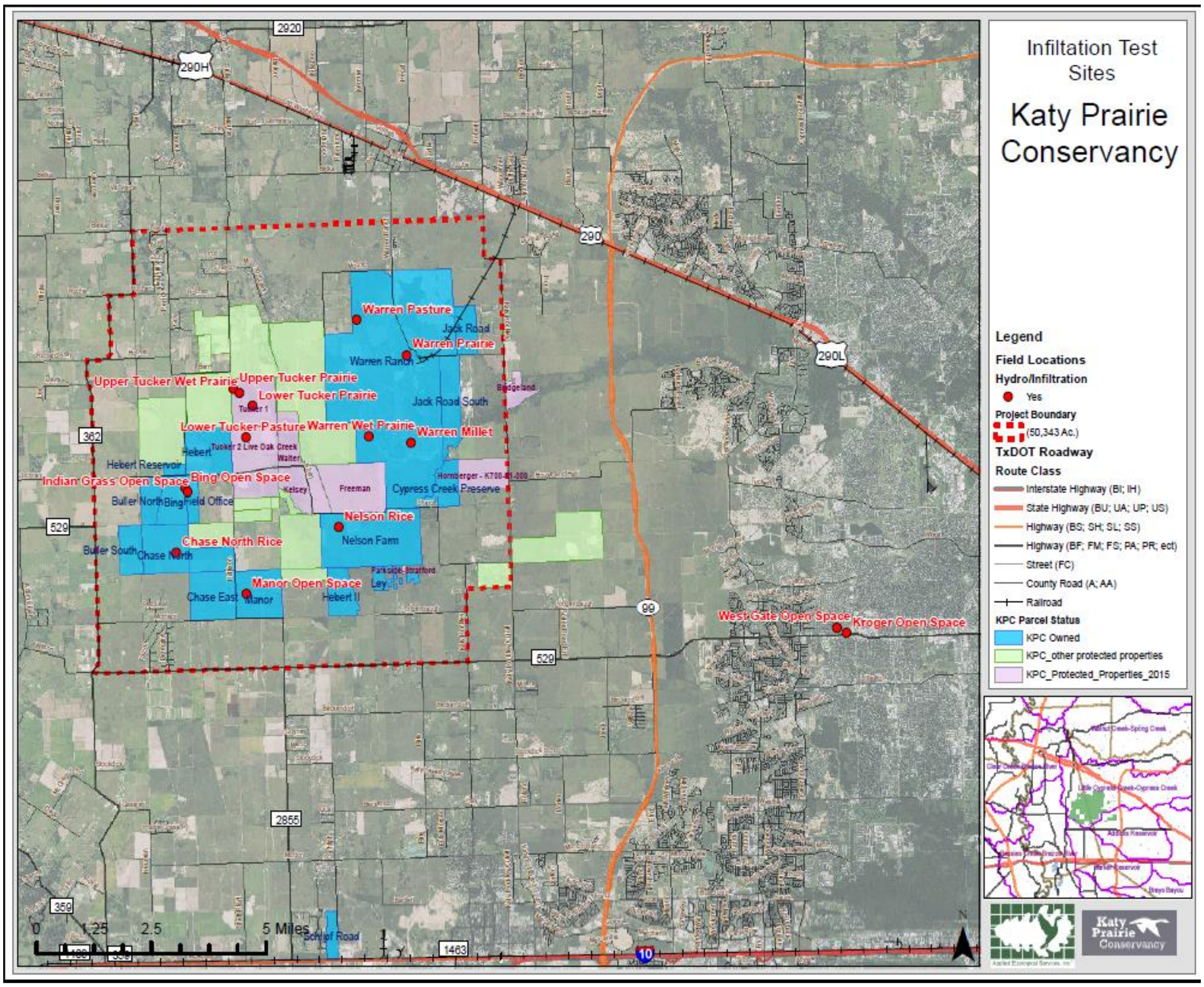


**Figure 3. Locations of the 15 Infiltration Test Sites**

The resulting three measured rates at each site were combined into a single K value for each site using geometrical (weighted) averaging. These average K values were then adjusted to eliminate the infiltration rate associated with the different soil types identified for each site, so that the remaining K value ($K_{veg}$) represented the infiltration rate associated with the particular vegetation type identified for each site, as shown in **Table 1**. The resulting $K_{veg}$ value for each of the different test sites was then used to obtain an average K value for each of the different land cover types ($K_{veg}$), as shown in **Table 2**. For those land cover types that did not have a test site to use in obtaining an average Kveg value (e.g. woodland), professional judgment was used, in consultation with AES and CPC, to estimate those values. This average K value for the different land cover types ($K_{veg}$) was then determined for the upper portions of the watershed where these different land cover types have been identified by AES, as shown in **Figure 4**.

**Table 1. Infiltration rates attributed to the vegetation type at each of the 15 test sites.**

| **Site Number** | **Name** | **Veg Type** | **Soil Type** | **Ksoil** (in/hr) | **Kveg,geo** (in/hr) | **Kveg,arith** (in/hr) |
|---|---|---|---|---|---|---|
| 5 | Kroger Open Space | Open Space | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 6 | West Gate Open Space | Open Space | Sandy Loam | 0.429 | **2.330** | **1.938** |
| 7 | Indian Grass Open Space | Open Space | Sandy Loam | 0.429 | **0.338** | **0.063** |
| 2 | Manor Open Space | Pasture | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 3 | Bing Open Space | Pasture | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 9 | Lower Tucker Pasture | Pasture | Loamy Sand | 1.177 | **7.883** | **8.338** |
| 12 | Warren Pasture | Pasture | Sandy Loam | 0.429 | **2.197** | **1.215** |
| 1 | Upper Tucker Prairie | Prairie | Sandy Loam | 0.429 | **4.456** | **3.794** |
| 4 | Lower Tucker Prairie | Prairie | Loam | 0.134 | **4.360** | **4.097** |
| 13 | Warren Prairie | Prairie | Loam | 0.134 | **5.495** | **8.576** |
| 10 | Nelson Rice | Rice | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 11 | Chase North Rice | Rice | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 15 | Warren Millet | Row Crop | Sandy Loam | 0.429 | **0.941** | **0.992** |
| 8 | Warren Wet Prairie | Wet Prairie | Loam | 0.134 | **0.903** | **1.288** |
| 14 | Upper Tucker Wet Prairie | Wet Prairie | Sandy Loam | 0.429 | **0.844** | **0.444** |

**Table 2. Final Infiltration rates, Kveg, for each land cover type**

| Land Cover Type | Kveg (in/hr) | Sites Averaged |
|---|---|---|
| Developed (Impervious) | 0 | No sites |
| Turf (Park Land) | 0.2 | 5 and 7 |
| Pasture-Shrub | 1.4 | No sites |
| Pasture-Grass | 0.7 | 2 and 3, 12 |
| Prairie | 4.8 | 1, 4 and 13 |
| Wet Grasslands | 0.9 | 8 and 14 |
| Rice Crops | 0 | 10 and 11 |
| Upland Crop | 0.9 | 15 |
| Woodland | 5 | No Sites |
| Water | 0 | No Sites |

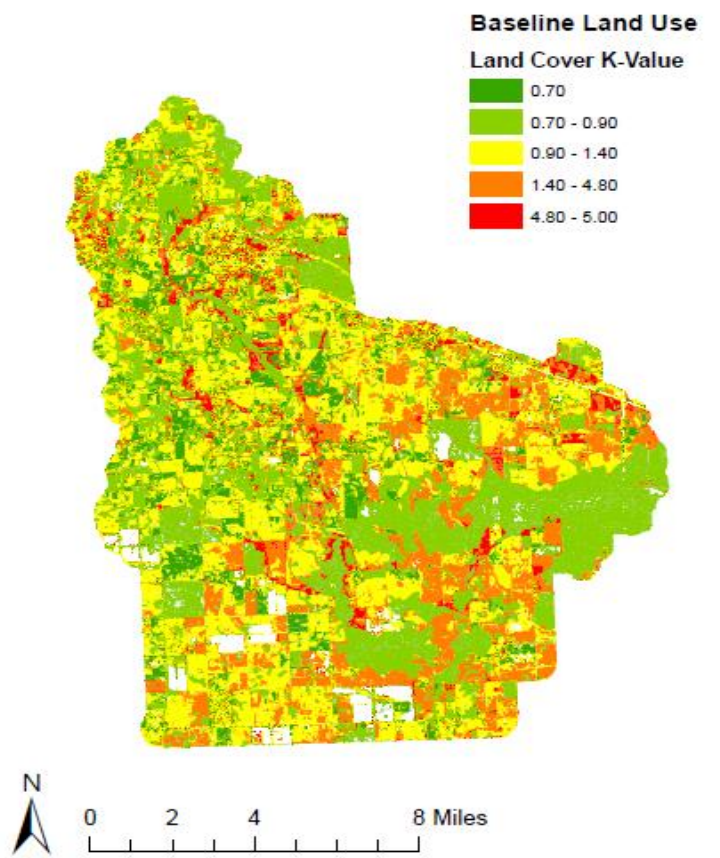


**Figure 4. Final Kveg values (in/hr) selected for the Upper Cypress Creek Watershed**

The final Kveg values shown in the figure above for the various land cover types throughout the Upper Cypress Creek Watershed were combined with the Ksoil values for these areas to arrive at a total K value for these areas that was used in the hydrologic modeling for determining the amount of infiltration for each area within the Upper Cypress Creek Watershed. The remaining portions of the watershed were modeled in the hydrologic model using only the Ksoil values based on the different soil types found in the various parts of the watershed, in accordance with the standard modeling approach.

## 4. Hydrologic Modeling of Different Land Cover Types

### 4.1 HMS

The existing hydrologic (HEC-HMS) model for the Cypress Creek Watershed was obtained from the HCFCD M3 library. This is the model that has been used to develop the various frequency flood flows throughout the watershed that are used to create the currently effective FEMA floodplain maps along Cypress Creek. The topographic data that was used to develop this model's input was based on the 2001 LIDAR, which has since been updated in 2008 and again in 2018. The land use data that was used to develop this model was based on 2004 conditions, and since then, there has been considerable amounts of new development that has occurred in the watershed, such as the Bridgeland Development in the upper portions of the watershed. Also, this HMS model was calibrated to past storm events, such as October 1994, October 1998 and the 2001 T.S. Allison. As such, there was a concern that this model may no longer be representative of the watershed's current hydrologic response to a storm event, given the amount of changes that have occurred to the land use, land cover and topography within the watershed. In order to investigate this concern, two recent storm events were evaluated with this HMS hydrologic model to determine if this model still could reasonably be representative of the hydrologic response of the Cypress Creek Watershed, especially in the upper portions of the watershed where the CPC lands are located. This HEC-HMS model was used to simulate the April and May 2016 storm events and its results were compared to the USGS stream gage data along Cypress and Little Cypress creeks. An example of these comparisons is shown in **Figure 5**. See **Appendix B** for more details.

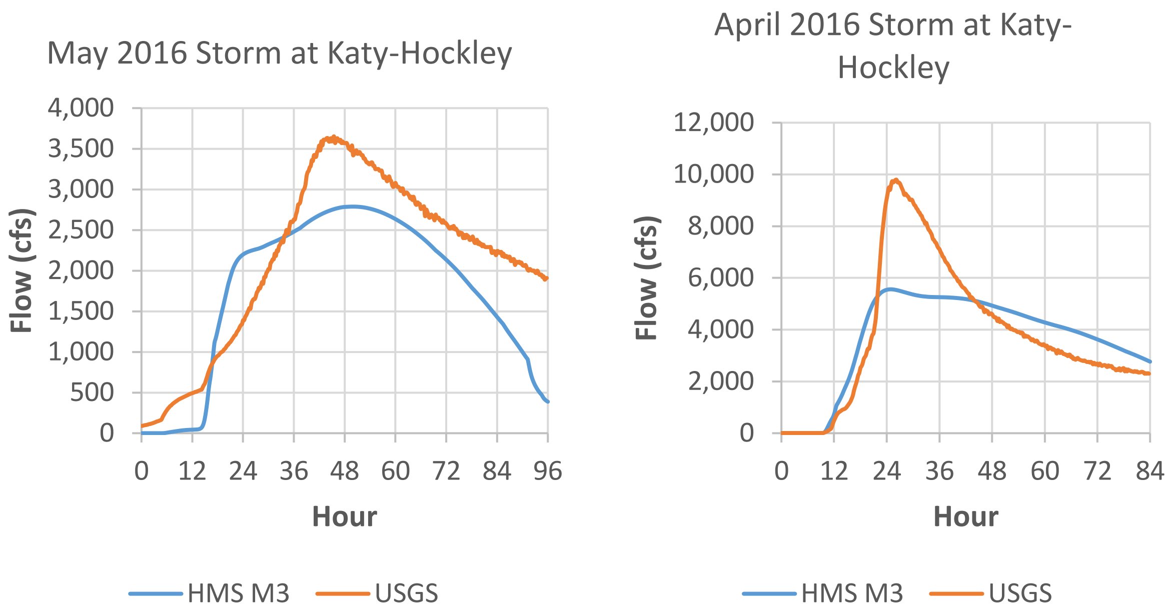


**Figure 5. HMS model results for the April and May 2016 storms at the Katy-Hockley gage**

As can been seen, there are inconsistencies between the observed data and the modeled data at the USGS gage location at Katy-Hockley, located in the upper portion of the watershed in the vicinity of the overflow area from Cypress Creek into the Addicks Watershed. Other comparisons show similar inconsistencies between the observed data and the modeled data for these two storm events at other USGS gage locations, such as at Grant Road and along Little Cypress Creek (see **Appendix B**). These results seem to confirm that this HEC-HMS hydrologic model from the HCFCD M3 library system no longer is a good representation of the current hydrologic response of this watershed, as observed peak flows are much higher than those predicted by the current HEC-HMS M3 modeling.

In addition, when investigating this model's input data, it was discovered that the K values (infiltration rates) used in the Green & Ampt method for calculating the amount of rainfall that is infiltrated into the underlying soils (with the remaining rainfall amounts becoming runoff) is representative of more "clay-like" soils (e.g. K = 0.079). This is inconsistent with the actual soil types in this watershed, which are predominately "sandy loam" (that have a Ksoil value of 0.43). This means that the HEC-HMS model from the HCFCD is going to generate much more runoff than if one were to use the infiltration rates associated with the actual soil types that have been identified for this watershed. This means that the HMS M3 model results discussed above should be even lower than they are shown to be, making the difference between modeled flow rates and observed flow rates even greater.

## 4.2 Vflo®

In order to obtain a better understanding of the impacts of these different land cover types within the upper portion of the watershed on the resulting runoff generated during various storm events, a hydrologic distributed model (Vflo®) was applied for the entire Cypress Creek Watershed, as a replacement to the HMS model from the HCFCD. A detailed description of this model and its development is contained in **Appendix C**. This hydrologic model uses the Green & Ampt method (the same as the HMS model) for calculating the amount of rainfall lost to infiltration, and the resulting amount that becomes runoff.

This Vflo® model was developed and calibrated to the April and May 2016 storm events in the Cypress Creek watershed. Details of the calibration of this model are provided in **Appendix C**. As can be seen in **Figures 6 and 7**, the resulting calibration results were fairly good, and much better than the HEC-HMS model was in reproducing observed flow hydrographs for these two recent storm events. However, this model was developed using the 2008 LIDAR data, as well as 2011 land use data (except for the Upper Cypress Creek Watershed that used the AES updated land cover data, as shown in **Figure 8**), along with K values reflecting more realistic soil types, for the entire watershed. It would thus be expected that this model would produce better results than the HEC-HMS model from HCFCD, given the limitations of outdated topographic data and land use data used in that model, particularly in the areas of the Cypress Creek overflow and the Bridgeland Development projects that lie just to the east of the main overflow area.

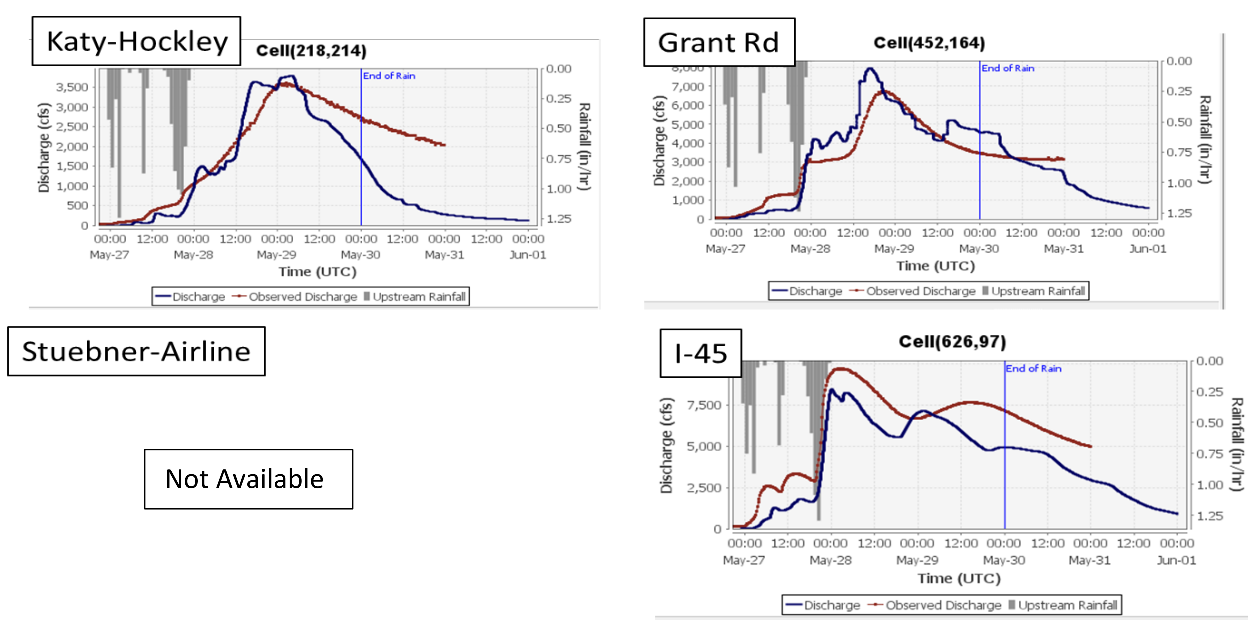


**Figure 6. Vflo® Calibration Results for May 2016 Storm Event at Selected USGS Gage Locations**

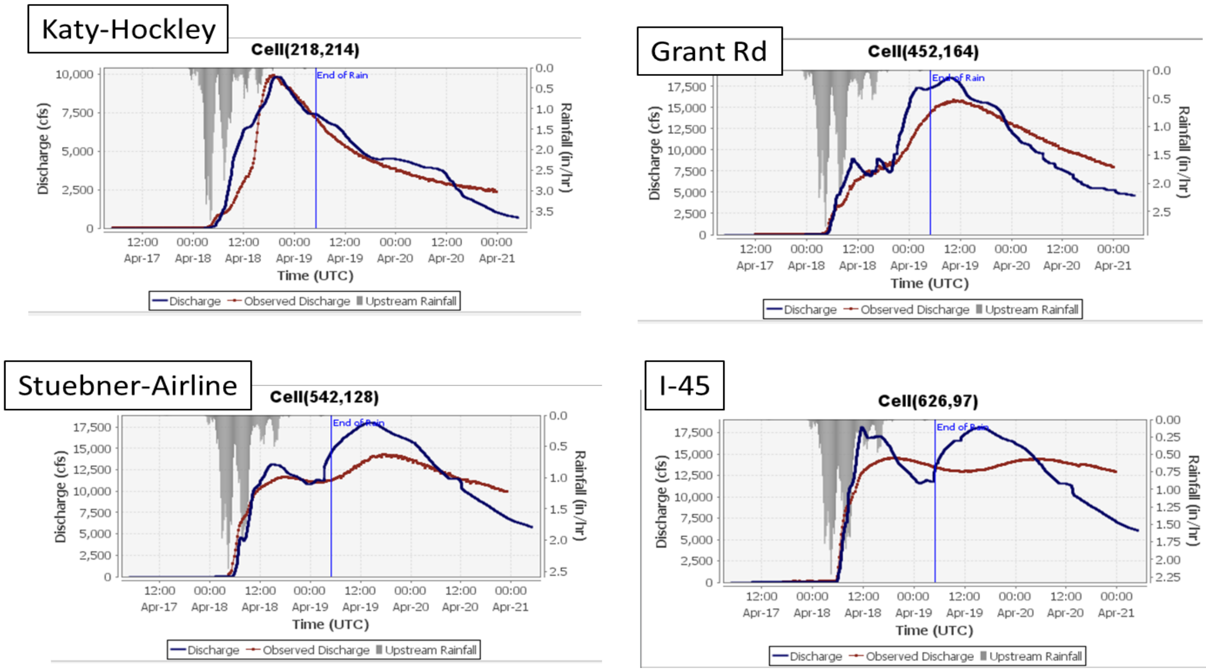


**Figure 7. Vflo® Calibration Results for April 2016 Storm Event at Selected USGS Gages**

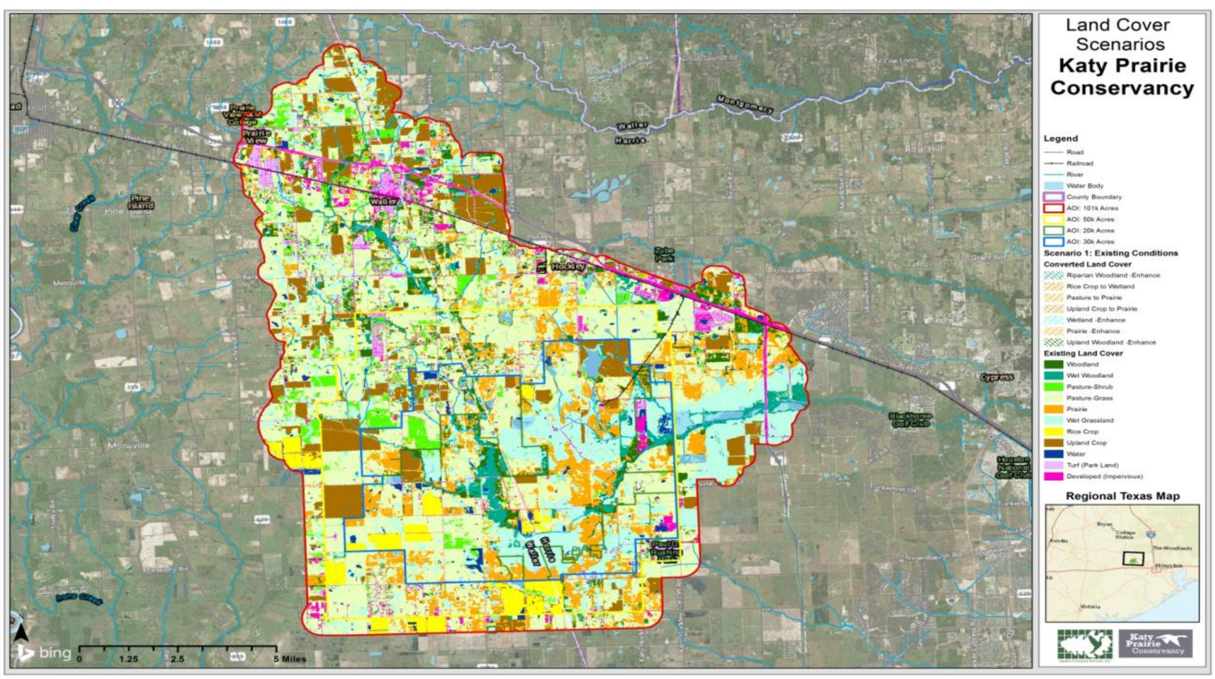


**Figure 8. Land Cover for Upper Cypress Creek Watershed (per AES)**

### 4.2.1 Land Cover Conversion Analysis

The calibrated Vflo® model was run for various frequency storm events. The resulting flows generated by the Vflo® model for the 2-, 5-, 10-, 25-, 50- and 100-year frequency storm events, represent "Baseline" or existing conditions (recognizing the limitations of the data available). Then, this model was modified to reflect four (4) different scenarios in which certain land cover types (pasture and upland crops) were assumed to be converted to native prairie, with a change in their corresponding Kveg values. The same frequency storm events were rerun in this model for each of these four scenarios, so that an evaluation could be made of the change in infiltration amounts that would be expected if such land cover conversion occurred.

As would be expected, as pasture and upland crop lands get converted to native prairie, the Kveg values increase for these converted areas, thus resulting in less of the rainfall becoming runoff as more infiltration is allowed to occur. However, it was discovered that a change in the infiltration rate does not always result in an equivalent amount of an increase in the total amount of infiltration that occurs during certain storm events. This is partly due to the available storage capacity in the soil for storing infiltrated water.

A sensitivity analysis was conducted using the Vflo® model on the amount of infiltrated water as a function of the soil depth. As would be expected, as the soil depth increases, the amount of rainwater that can be infiltrated increases and the runoff volume decreases, so long as the infiltration rate is not the limiting factor. **Table 3** shows a summary of the results of this analysis for different soil depths for the various storm frequency events (pre-Atlas 14). Since soil depth plays a big role in determining the amount of infiltration, further study is needed in assessing this, and how native prairie vegetation might increase the effective soil depth.

**Table 3: Summary results of Vflo®® analysis showing Reduction in Runoff Volume in ac-ft/ac converted**

| | | **Soil Depth** | | | | |
|---|---|---|---|---|---|---|
| **Frequency Event** | **Rainfall (24-hr)** | 12 in | 18 in | 24 in | Unconstrained | Real Data |
| Storm | Rain (in) | ac-ft/converted acre | ac-ft/converted acre | ac-ft/converted acre | ac-ft/converted acre | ac-ft/converted acre |
| 2 | 4.1 | 0.0028 | 0.0028 | 0.0028 | 0.0028 | 0.0026 |
| 5 | 5.8 | 0.0032 | 0.0280 | 0.028 | 0.028 | 0.0110 |
| 10 | 7.1 | 0.0010 | 0.0533 | 0.053 | 0.053 | 0.0273 |
| 25 | 9 | 0.0009 | 0.010 | 0.108 | 0.108 | 0.0458 |
| 50 | 10.6 | 0.0009 | 0.005 | 0.105 | 0.15 | 0.0285 |
| 100 | 12.4 | 0.0010 | 0.002 | 0.042 | 0.20 | 0.0090 |

The resulting flow hydrographs from the Vflo® modeling were used as input to the HEC-RAS 1D/2D hydraulic model for Cypress Creek, as discussed in the following section.

## 5. Hydraulic Modeling of Overflow Area along Cypress Creek

The existing hydraulic model (HEC-RAS) for Cypress Creek was obtained from the HCFCD's M3 library for use in developing the HEC-RAS 1D model to be used for this study. The HCFCD hydraulic model is a steady state model that takes as input to the model (1) the geometry of the creek's channel and overbank areas at selected cross-sections along the creek; (2) the Manning's n-values for portions of each cross-section to reflect the roughness of the creek and the overbank areas that cause resistance to the flow of water; and (3) the peak flow rate along the creek that is computed by the hydrologic model for the various frequency or historic storm events. This hydraulic model that was obtained from the HCFCD is the model that was used to create the existing (currently effective) FEMA floodplain maps for Cypress Creek. This model utilized the 2001 LIDAR data for its geometric information, as well as surveyed bridge information obtained in the early 2000s. Thus, to the extent that any of this information has changed over the years, this model may not necessarily be representative of the hydraulic response of the creek and its overbank areas under current conditions. This appears to be the case, based on a comparison of the high water marks from the April 2016 event as compared to the flood profiles developed for the FEMA floodplain mapping of Cypress Creek, as shown in **Figure 9**.

For example, while it appears that along most of the upper portions of the creek the high water marks correspond closely to the 500-year flood profile, there is an area in the vicinity of the Bridgeland Development (Stream Station 17000) where the high water marks are more closely aligned with the 100-year flood profile. It is known that the Bridgeland Development has constructed some detention areas along Cypress Creek that may have altered the hydraulic response of the creek in this area.

In order to better simulate the hydraulic response of the creek and its overbank areas to runoff entering this system, it was decided to develop an unsteady HEC-RAS 1D model using the information obtained from the HCFCD's HEC-RAS steady-state model. In addition, in order to better simulate the overflow from Upper Cypress Creek into the Addicks Watershed, a HEC-RAS 2D model was developed for the overflow area and coupled with the 1D model (see **Figure 10**). The 2D portion of the HEC-RAS model is shown as the green area in Figure 10.

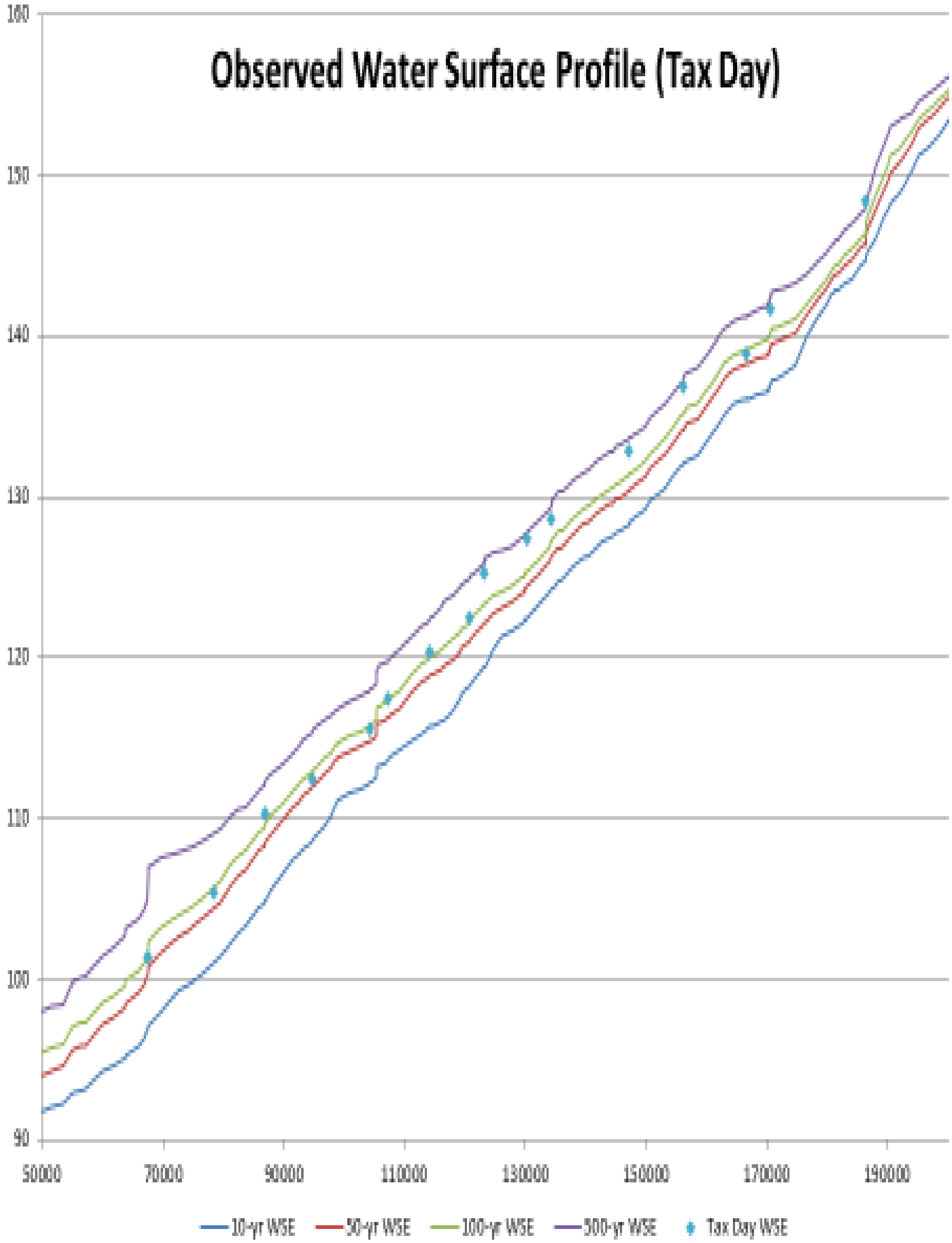


**Figure 9. Flood Frequency Profiles of Cypress Creek compared to the April 2016 Flood Event**

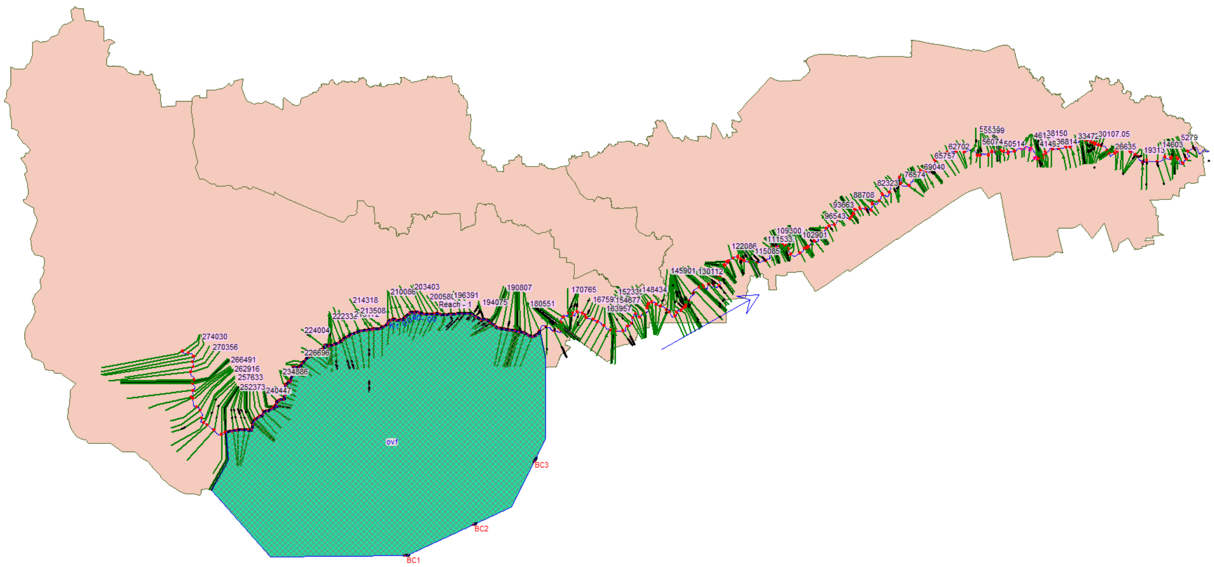

**Figure 10. Schematic of the HEC-RAS 1D/2D model of Cypress Creek (overflow area in green)**

A more detailed discussion of the development of this HEC-RAS 1D/2D model is presented in **Appendix D**. This RAS model utilized the flow hydrographs generated by the Vflo® model as input at various locations along the creek, and then the RAS model was used to combine and route these various flows along the creek to simulate the movement of these flood flows along Cypress Creek. The output from this RAS 1D/2D unsteady state model includes the flow and water level over time at the various cross-sections along the creek that are represented in the model, including the overflow area**. Figure 11** shows the resulting floodplain area using this HEC-RAS 1D/2D model for the 100-year frequency storm event (pre-Atlas 14).

There is not a very wide floodplain along Cypress Creek, except in the upper portions, such as in the vicinity of the CPC lands and the overflow area. These wide floodplain areas are due to the high flow rates from upstream, entering the flatness of the CPC and overflow areas.

In addition, this HEC-RAS 1D/2D model was used to simulate the HCFCD's Management Plan 5, a proposed berm system within the overflow area of upper Cypress Creek. Limited information was available from the HCFCD regarding the details of their proposed berm system, in particular the details of the outlet structures associated with this proposal, such as at Cypress Creek and Bear Creek. As such, an assumed outlet structure was incorporated into this RAS 2D model for both Cypress Creek and Bear Creek, and the resulting impoundment behind this berm system was determined for both the 100-year and 500-year storm events (pre-Atlas 14). See **Figure 12** for the inundation associated with the 100-year storm event with the proposed Management Plan 5 berm and outlet system in place.

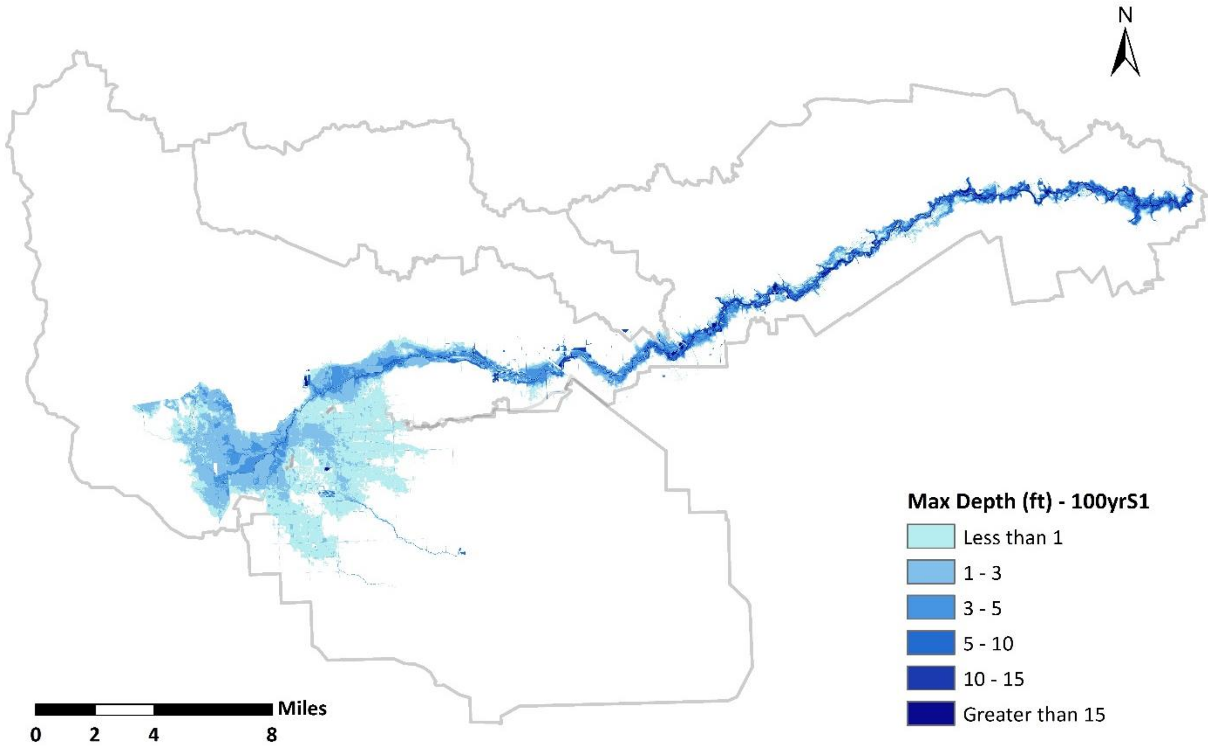


**Figure 11. Floodplain for 100-year Storm Event along Cypress Creek, including overflow area**

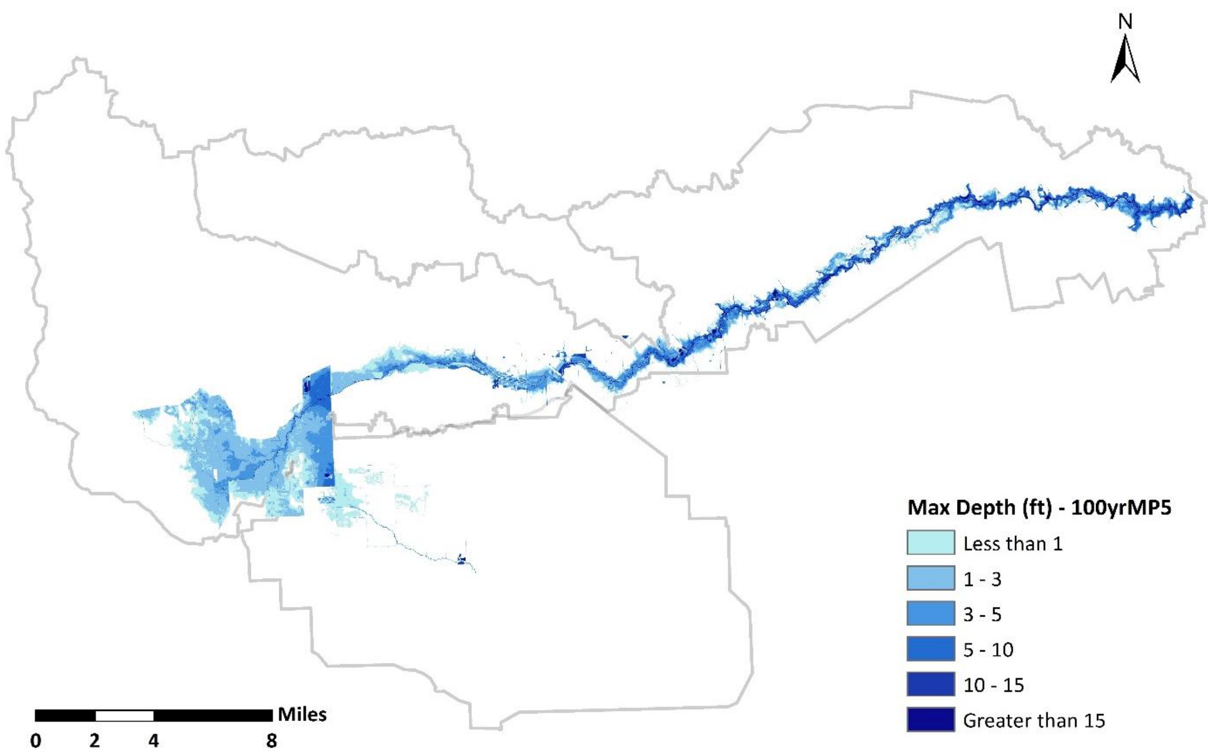


**Figure 12. 100-year Inundation with Management Plan 5 Berm and Outlet Structures in Place**

# 6. Summary of Results – Field Studies and Hydrologic and Hydraulic Modeling

## 6.1 Infiltration Tests

The infiltration tests that were conducted for this study produced infiltration rates, or Kveg values, for different types of land cover, such as pasture, prairie, and open space/developed areas. The results from these tests were used to assign Kveg values for the different land cover types in the upper portions of the Cypress Creek Watershed, including the CPC lands. As was expected, the Kveg values for prairie were found to be much higher than for pasture (4.8 in/hr versus 0.7 in/hr). These Kveg values were then used in the hydrologic modeling of the watershed response to various frequency rainfall events.

The hydrologic modeling of the various frequency storm events using Vflo®, a distributed model, showed the change in runoff and infiltration with different infiltration rates that were assigned to different land cover types. This modeling work showed that the infiltration rate for native prairie, which is much higher than for other land cover types, such as pasture or developed grassland, would produce much lower runoff amounts and much higher infiltration amounts than the other land cover types. However, the soil depth, or the amount of storage capacity in the soil, can be a limiting factor in the amount of infiltration that can occur during various storm events, especially for the more infrequent or higher frequency storms. Different scenarios of converting pasture and upland crops to prairie were simulated in the Vflo® model to demonstrate the impacts on runoff and infiltration volume and the resulting flow rates entering Cypress Creek in the upper portions of this watershed.

These different scenarios of converting pasture and upland crops to prairie involved different sized areas within the Upper Cypress Creek Watershed. For example, the general area of the CPC lands (approx. 20,000 acres) was analyzed involving about 7,830 acres (about 40%) of existing land cover being converted to prairie. Another scenario, including an expanded area around the CPC land (approx. 30,000 acres), was analyzed involving about 11,635 acres (about 40%) of existing land cover being converted to prairie. A third scenario, including even more land around the CPC land (approx. 50,000 acres), was analyzed involving about 21,215 acres (about 40%) of converted prairie. Finally, a scenario including the upper portion of the Cypress Creek Watershed (approx. 100,000 acres) was analyzed involving about 44,325 acres (about 45%) of converted lands becoming prairie. The results of all of these land-use conversion scenarios showed that the amount of rainfall that would be infiltrated into the underlying soil increased when converting existing land cover types like pasture to native prairie, with a corresponding decrease in the amount of rainfall that became runoff and contributed to downstream flooding. Depending on the soil depth, this infiltration rate could increase by as much as 0.2 acre-feet per acre of converted land cover type for the 100-year storm event (12.5 inches in 24 hours), as shown in **Figure 13,** assuming the soil is unconstrained**.**

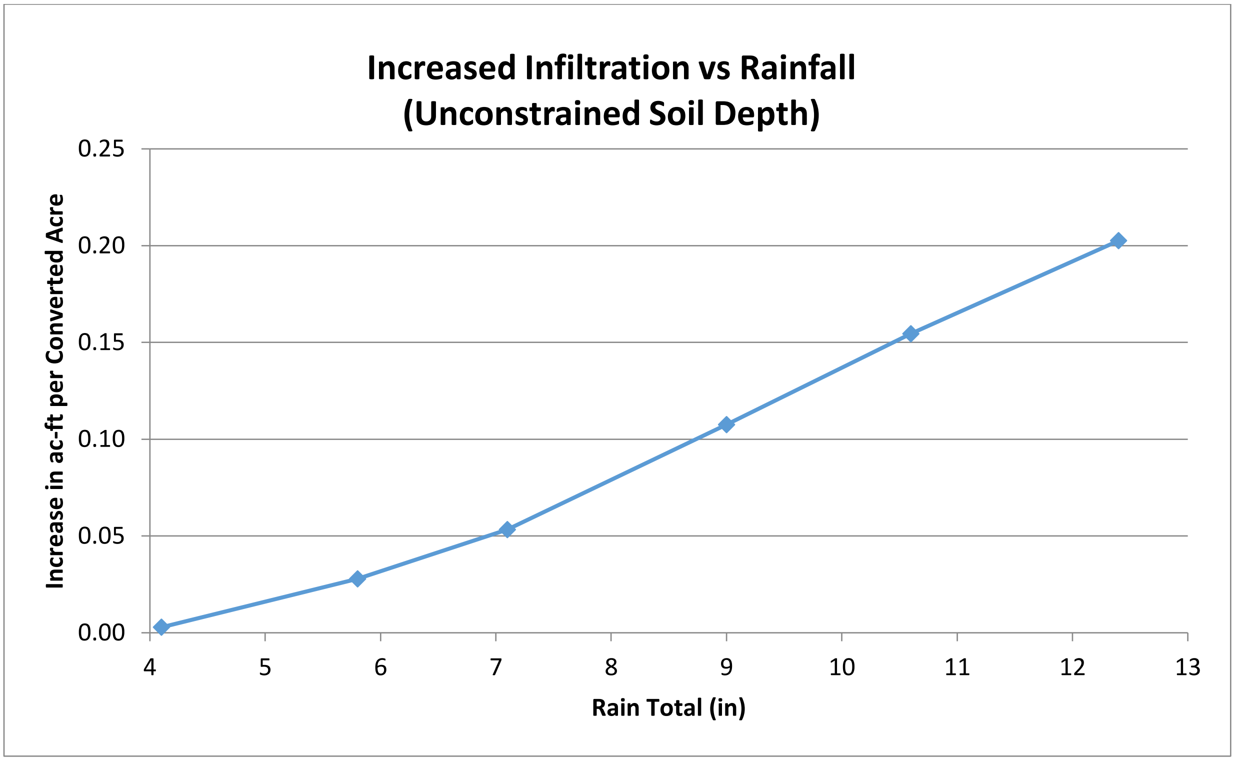


**Figure 13. Increased Infiltration per Converted acre vs. Rainfall (unconstrained soil depth)**

The infiltration rates are highly dependent on the soil depth. There is a shallow "clay pan" layer underneath the surface of the ground that acts as a barrier to allowing additional infiltration. This "clay pan" layer is about 12"-24" below the surface, in the vicinity of the upper Cypress Creek Watershed. As such, the amount of increased infiltration that can be attributed to converting to native prairie vegetation is limited. However, there is literature indicating that native prairie vegetation can penetrate this clay pan layer with its roots, thereby allowing for more infiltration into that clay layer. Further research is needed to investigate this for the soils in the upper Cypress Creek Watershed.

The stormwater runoff flow rates entering Cypress Creek as computed by the hydrologic model, Vflo®, for certain frequency storm events were inputted into a hydraulic model, HEC-RAS 1D/2D, to allow for the computation of flows and water levels along the creek and through the overflow area into the Addicks Watershed. This 1D/2D model was also used to simulate the inundation associated with a proposed berm system, known as Management Plan 5, as shown in **Figures 11 and 12**.

## 6.2 Detention Storage Benefits of Native Prairie

In addition to the enhanced infiltration, and hence reduced runoff volume, provided by native prairie vegetation, prairie vegetation inhibits overland flow of rainfall runoff, which imparts a slowing, detention-like effect. This natural detention provides an additional reduction in flooding downstream. In order to quantify the amount of detention being provided by native prairie vegetation, the Vflo® model was used to simulate the rainfall-runoff response to different vegetation types in the 100,000-acre area of Upper Cypress Creek Watershed (outlined in black on **Figure 14).**

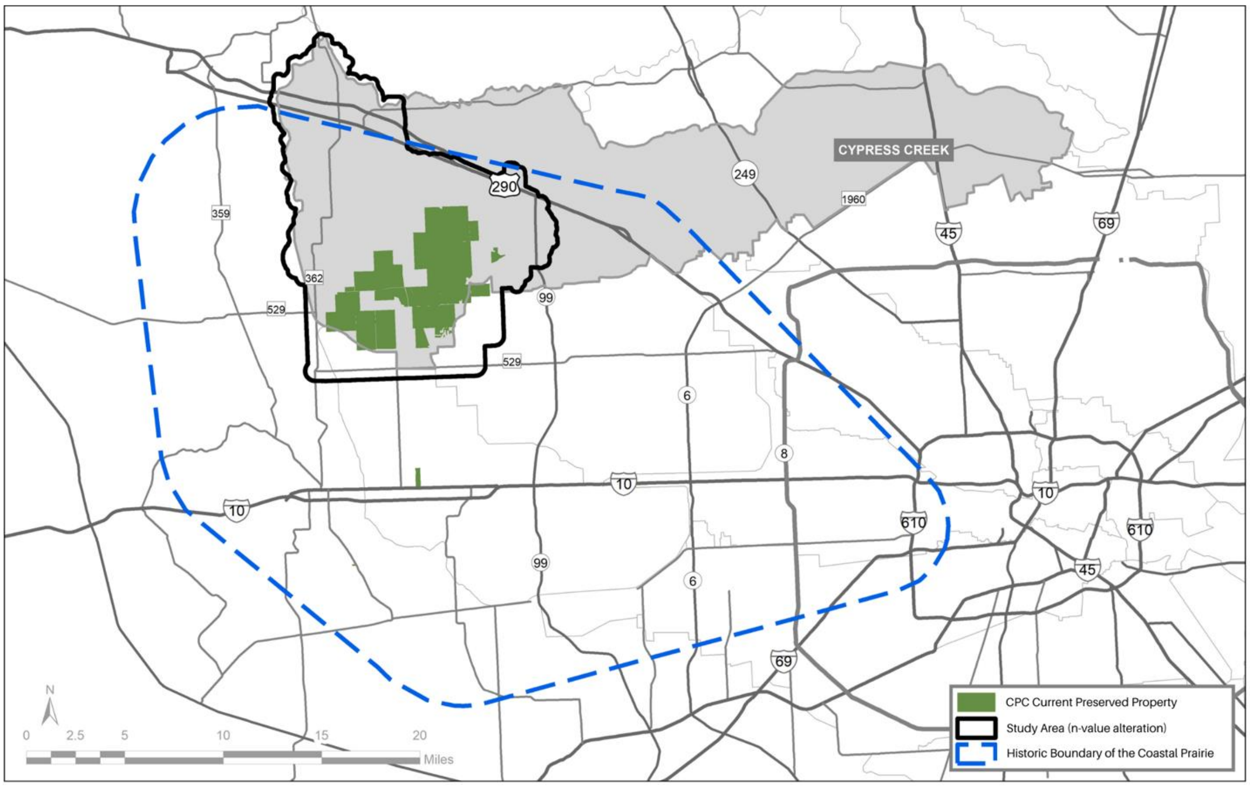


**Figure 14. Study Area for Evaluating Detention Effects of Different Vegetation Types**

Evaluation of the hydrologic model response to different types of vegetative cover was made at various locations along upper Cypress Creek for a range of statistical storm events (small volume – large volume). The results showed significant reduction in peak flow and delayed timing under conditions of increasing prairie vegetation, represented in the model by changing the Manning's roughness coefficient. In evaluating the model under four storm scenarios, the results showed prairie vegetation (with a Manning's n-value of 0.6) would generally have a more dominant impact on slowing rainfall-runoff during smaller volume storms (2-year or 10-year storms) than a 0.2% (500-year) storm event, as expected. However, there is still a significant reduction in peak flood flows for the larger storm events, as shown in **Figure** E-2. **15**. For small catchment size areas, such as less than about 5 square miles, the peak flow reduction can be as much as 50% or more, even for the larger storm events, when converting from the current land cover conditions to native prairie vegetation.  For larger catchment areas involving the Cypress Creek channel, less decrease is shown due most likely to a combination of timing of the peak flows entering the channel and the natural floodplain storage along the creek.

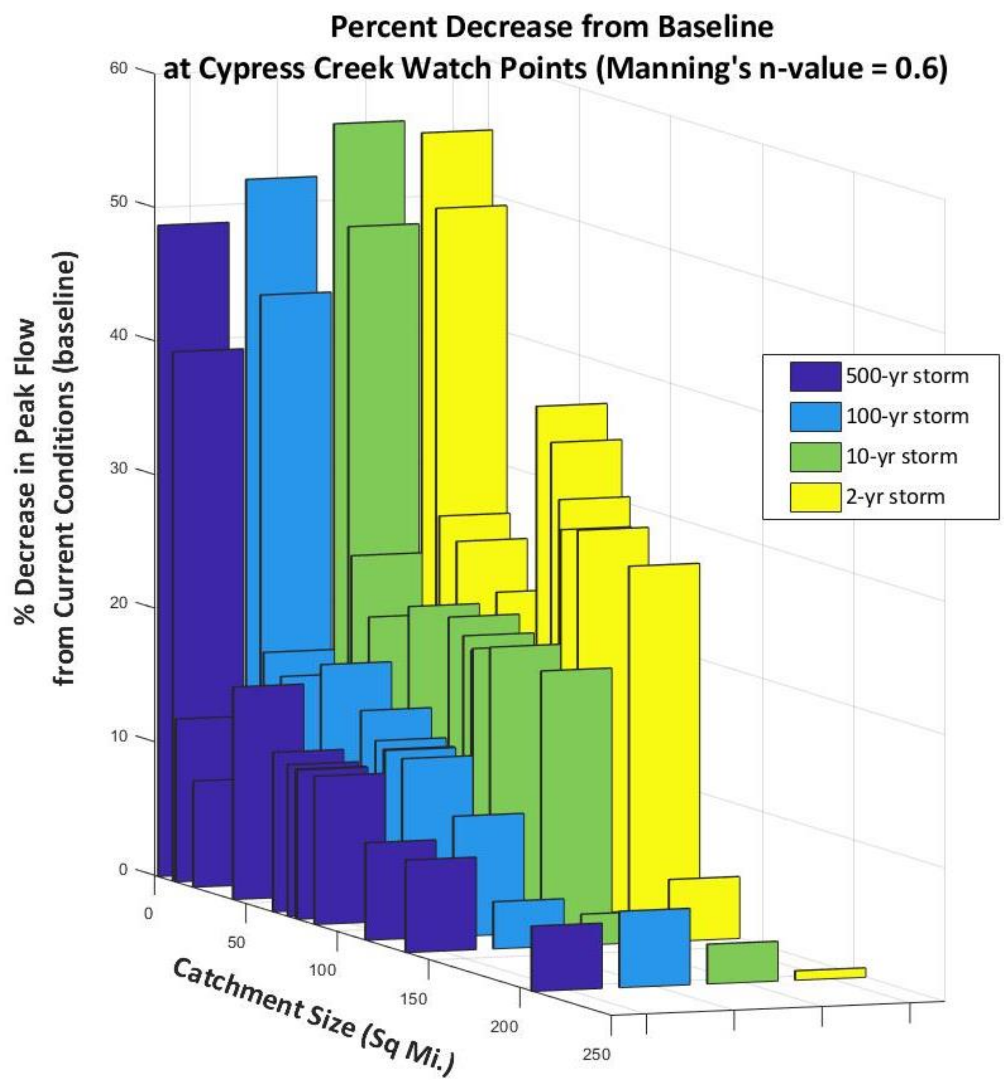


**Figure 15.  Decrease in Peak Flow from Current Conditions by Restoring Area to Native Prairie**

To understand how the detention storage benefits provided by coastal prairie vegetation compares to HCFCD detention standards for new development, hydrographs and runoff rates were analyzed both along the channel and corresponding to overland catchments from the *Vflo®®* modeling results. In assessing the hydrographs at various points corresponding to moderate -scale overland catchments under three different land use scenarios: developed/cleared plot with n-value of 0.1; current land cover with n-value averaging about 0.35; and native tallgrass prairie with n-value of 0.6, it was confirmed that vegetative roughness imparts a slowing effect mimicking that of an engineered detention pond during rainfall events.

**Figure** E- 5. **16** shows on the left side how a typical detention storage pond affects the peak flow after it enters the pond by reducing the peak flow as it exits the pond and delaying the timing of the reduced peak flow. On the right side of the figure, typically the peak flow for a cleared lot (developed with 0% imperviousness) is high, since there is virtually no storage of runoff water being provided as it moves across the surface of the plot. This peak flow is reduced, however, when other vegetative types are involved (current conditions), and is reduced even more when native prairie vegetation is the land cover type, due to the detention-like process of how runoff is slowed as it is conveyed across the surface of such land. Through this relationship, the detention storage capacity of prairie vegetation can be quantified numerically as the difference between the developed/cleared plot hydrograph and the hydrograph of the current conditions or full prairie restoration scenario.

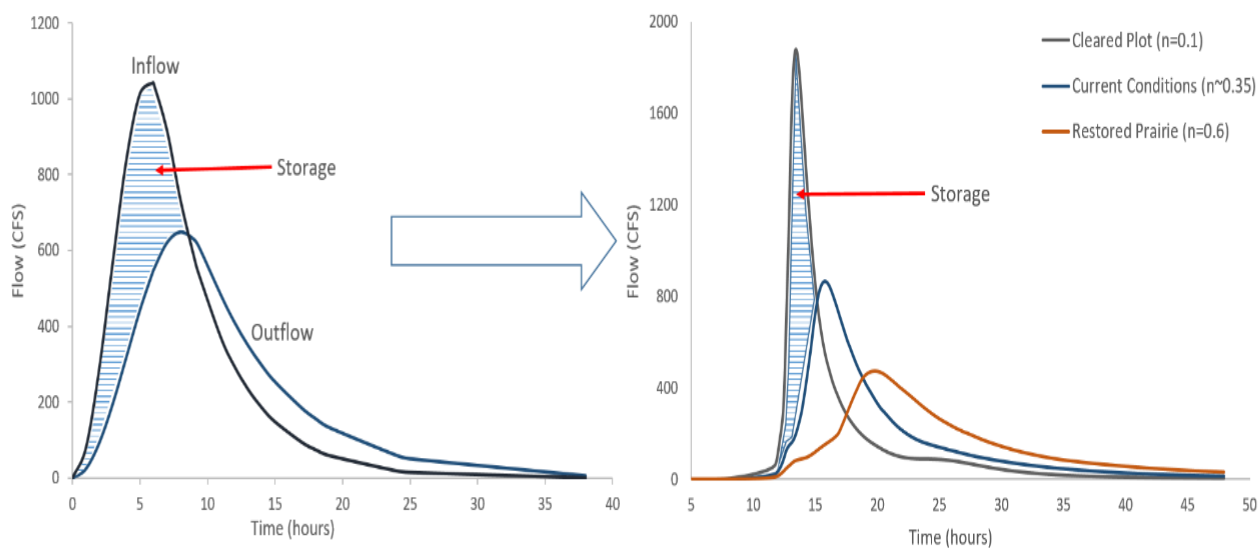


**Figure 16. Comparison of peak flow reduction due to typical detention pond (left) and different land cover types (right)**

The shaded area between the hydrographs represents the amount of detention storage volume provided to produce the reduction in peak flow shown. The detention storage volume amounts were assessed at five points along main Cypress Creek and 6 overland catchments within the region of n-value change to both summarize the detention capacity and analyze corresponding spatial variability. The overland catchments varied in size from 280 acres to 915 acres with average slopes between 0.5 -3 %. The average detention capacity in acre-ft/acre created by the influence of overland roughness due to different land cover types is summarized in **Table 4** for both current conditions and native prairie conditions as compared to the developed scenario.

**Table 4. Detention Storage in Acre-feet/acre provided by Different Land Cover Types**

| | *Current Conditions* | | *Prairie Restoration/Expansion* | |
|---|---|---|---|---|
| *Storm Size* | *Localized Overland Catchment* | *Channel Catchment* | *Localized Overland Catchment* | *Channel Catchment* |
| *10-yr Atlas 14* | 0.16 | 0.06 | 0.24 | 0.12 |
| *100-yr Atlas 14* | 0.37 | 0.12 | 0.58 | 0.25 |

The average storage volumes shown above were considered adequate in capturing the general storage capacity because there was little variability in calculated storage volume between points at both overland and channel catchments (standard deviation less than 0.057 acre-ft/acre for 10-yr and 100-yr storm sizes). However, a significant difference in storage capacity is seen at the channel catchment points compared to localized overland catchments due to the channel floodplain storage effects reducing the influence of overland roughness on rainfall-runoff peak flows after they enter the channel.

To compare the detention storage provided by native prairie vegetation to HCFCD detention requirements for new development, hydrographs were generated using the HCFCD site-runoff curves and the Small Watershed Method (for catchments smaller than 640 acres). Explanation of the HCFCD methodology can be found in the Harris County's Drainage Criteria Manual. Using this method, hydrographs were generated for HCFCD's fully developed condition (85% impervious cover) and HCFCD's "pre-development" condition (0% impervious) for the 100-year storm and were compared to some modeled hydrographs for equivalent-sized catchments associated with different land cover types.

The detention storage volume needed to mitigate for a fully developed catchment area was calculated for both the modeled hydrographs and those generated by HCFCD's methodology (**Figure 17**). The results showed that the pre-Atlas 14 HCFCD detention requirements for a fully developed site (up to 85% impervious) was 0.55 acre-feet/acre to bring the peak flow back down to the 0% impervious value, considered by the HCFCD to be the "pre-development" or "undeveloped" condition. This compares to the 2019 post-Atlas 14 HCFCD requirement of 0.65 acre-feet/acre for detention storage for small developments that do not use modeling to determine its detention storage needs. The same detention rate (about 0.62 ac-ft/ac) as these HCFCD criteria was found to be necessary from the hydrologic modeling for bringing the 85% impervious cover fully developed condition peak flow down to the 0%

impervious “urbanized/clear lot” condition (using an n-value of 0.1). However, additional detention storage was needed (totaling about 1 ac-ft/ac) to bring the peak flows from the 85% impervious fully developed condition down to the undeveloped “current condition”, and even more so (about 1.15 acre-feet/acre) to bring the developed peak flow down to the undeveloped, full “native prairie” condition. From this comparison, it was concluded that HCFCD’s site-runoff curves assume a well-drained, cleared and grassy site as its “undeveloped” or 0% impervious scenario, which fails to account for the effects of converting natural vegetative cover to a cleared, grassed plot. Additional detention storage (another 0.5 ac-ft/ac) would thus need to be provided beyond the HCFCD minimum of 0.65 acre-ft/acre if one were developing a prairie landscape and needed to provide full mitigation for the loss in natural detention storage. This is an indication that if developing a coastal prairie landscape, specifically the CPC land, according to Harris County 2019 developmental regulations, the resulting rainfall-runoff generated by the new development will be significantly increased in the downstream watershed area if only the minimum required detention storage is provided.

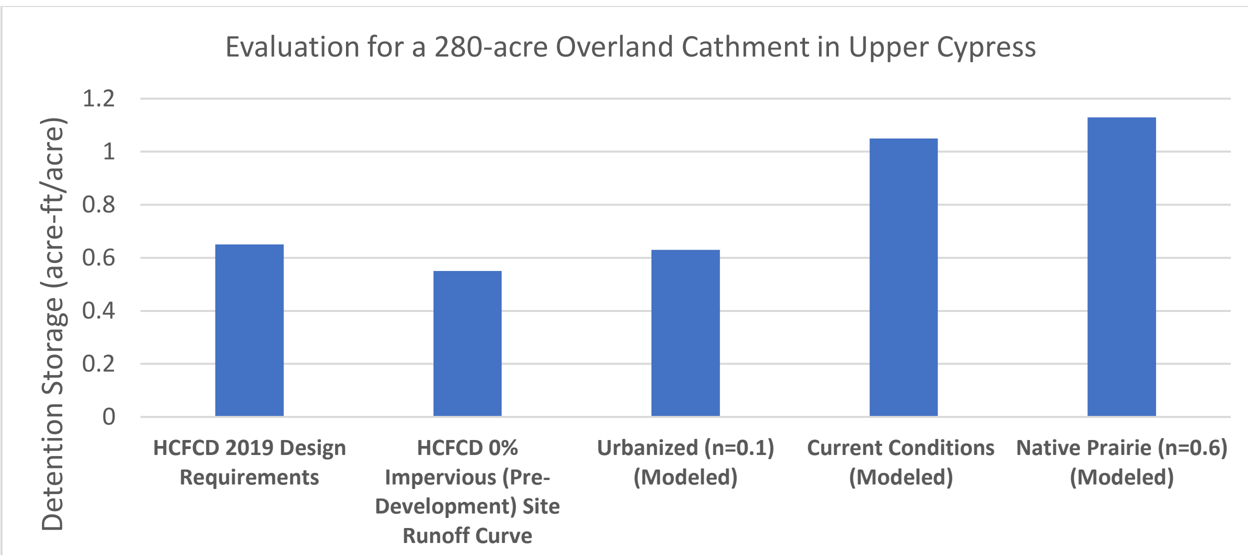


Figure 17. Detention Storage Required to Mitigate a Fully Developed Catchment under HCFCD rules versus Different Land Cover Types

In altering the Manning’s roughness coefficient, this study aimed at determining the *relative* impact of overland vegetation on above-ground detention-like effects. However, this was done without considering the effects on infiltration and depression storage, which together have a large retention effect of prairie vegetation that has not been included in this detention analysis. As discussed in the literature and subsequently verified by a recent field infiltration study conducted by the SSPEED Center on CPC land, as discussed earlier in this report, prairie vegetation can increase water-retention capacity of topsoil. A prairie expansion would therefore theoretically increase the reduction in peak flow demonstrated by the expansion scenario in this study. Information regarding infiltration estimates relating to the current conditions of different land cover types of undeveloped lands is discussed earlier in this report, and can be found in **Appendix A**.

## 6.3 Depression Storage Benefits of the Katy Prairie

This study attempted to quantify the retention and detention storage potential of terrain depressions, inherent to coastal prairie landscapes, by employing a 2D HEC-RAS model. Depressions are known to influence the overland flow dynamics and overall floodplain response of prairie watersheds and watersheds with marshes and wetlands (depressions). There is ongoing research in hydrologic modeling to categorize and represent depressions appropriately in distributed hydrologic models to enhance overall model response accuracy. However, development of this methodology has yet to be applied to quantify the rainfall-runoff storage potential of depressions in a floodplain. This study was an attempt to understand 2D hydraulic modeling, as opposed to hydrologic modeling, as a tool to analyze the influence of natural, coastal prairie overland terrain in urban flood mitigation.

**Figure 18** exhibits a schematic of the potential impact of depressions on rainfall runoff as compared to flat terrain without depressions.

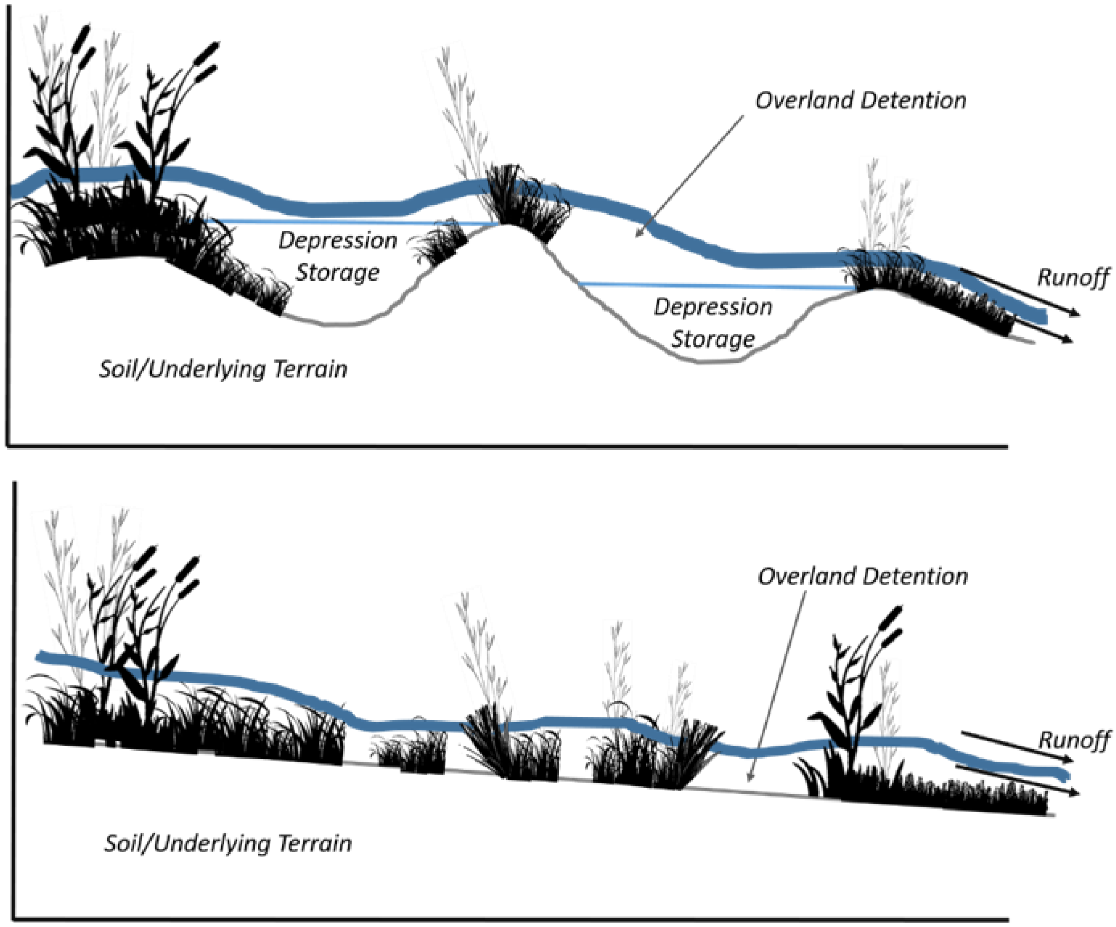


Figure 18. Diagram of Rainfall-Runoff Behavior with Depressions in Topogrpahy (top) versus Flat Terrain with No Depressions (bottom)

Shown in this figure is the theoretical behavior of detention storage provided by overland vegetation, discussed in the previous section, and depression storage provided by depressions in the landscape. This type of depression storage can provide an additional detention/retention effect by slowing the rainfall-runoff as it can move from one depression to the next before reaching the watershed outlet or a river reach (similar to a maze). In a topography with depressions, when the rainfall-runoff subsides, water can remain in the depressions and thus be retained, to eventually infiltrate or evaporate.

Below in **Figure 19** is an image from the Katy Prairie region in 1940; highlighted in orange are terrain depressions that, at the time of imagery capture, were filled with water making them easily discernable in the image. Subsequent, available, Google Earth images do not show the depressions as distinctly, making it a question of whether the depressions are still as abundant in the region, or if they have been eroded or filled in due to land use changes over time. The 2D RAS model served as a tool to investigate the presence of depressions and visualize the movement of runoff through depressional topography (based on the 2018 Lidar) as a time-series after a rainfall event. The 10-yr, 100-yr and 500-yr NOAA Atlas 14 24-hour design storms were simulated as rain-on-grid, and the spatial distribution of the runoff was analyzed in ArcGIS at 12-hour increments post rainfall.

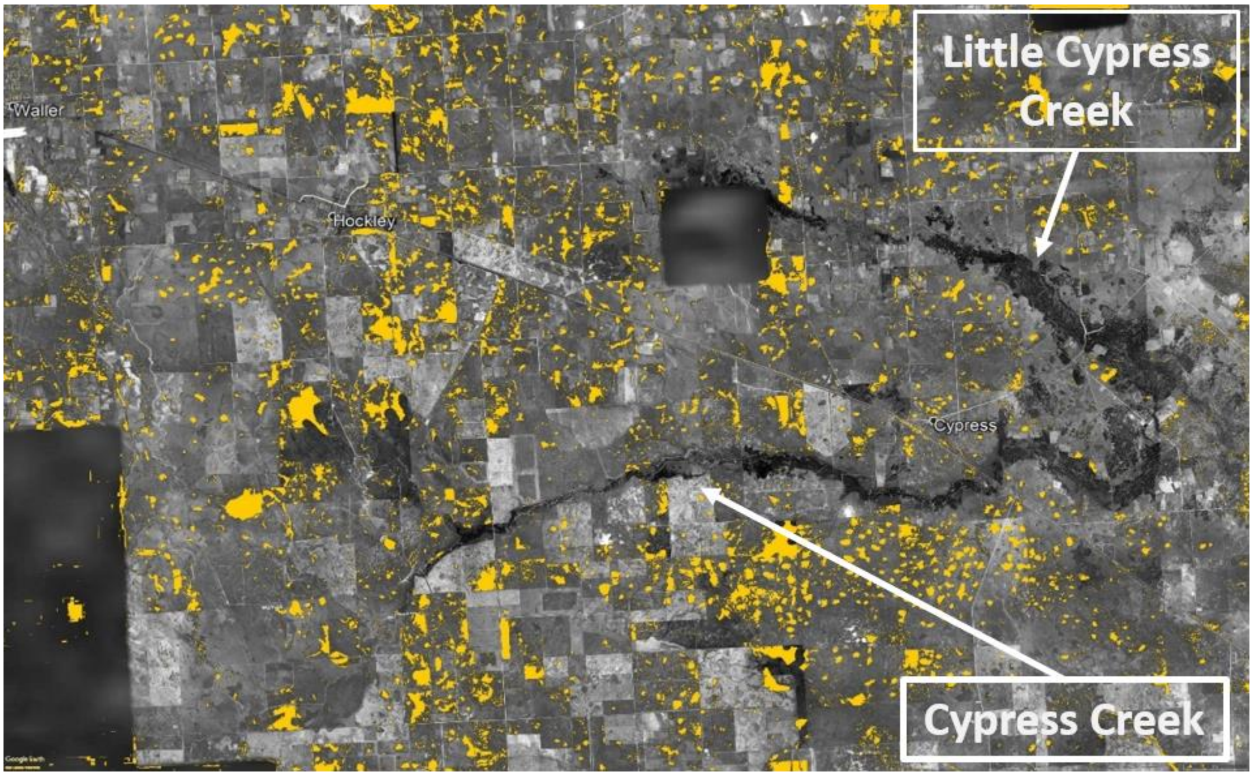


**Figure 19. 1940 Aerial of Upper Cypress Creek Watershed showing surface depressions (in yellow)**

Related to detention storage and terrain depressions, retention storage refers to water that is kept against the force of gravity above the soil until it is eventually infiltrated or evaporated back into the hydrologic cycle. To evaluate the retention storage in the depressions in the Upper Cypress Creek Watershed, the domain of the 2D HEC-RAS model was restricted to the sub-watershed divide of Cypress Creek to force water, which would naturally overflow into the Addicks Watershed on the southern border, to instead continue to flow downstream to a single outlet. A 24-hour design storm hyetograph was used as a precipitation boundary condition over the model domain, and the model was run until all water within the channel had left through the downstream outlet. Any rainfall remaining in the model domain was therefore considered retained in overland depressions (including ponds, lakes and engineered detention) represented in the Lidar-based topography.

Calculation of the retained volume was restricted to the undeveloped portion of the watershed including CPC property and an additional land south of highway 290 (**Figure 20**), approximately 80,000 acres in total.

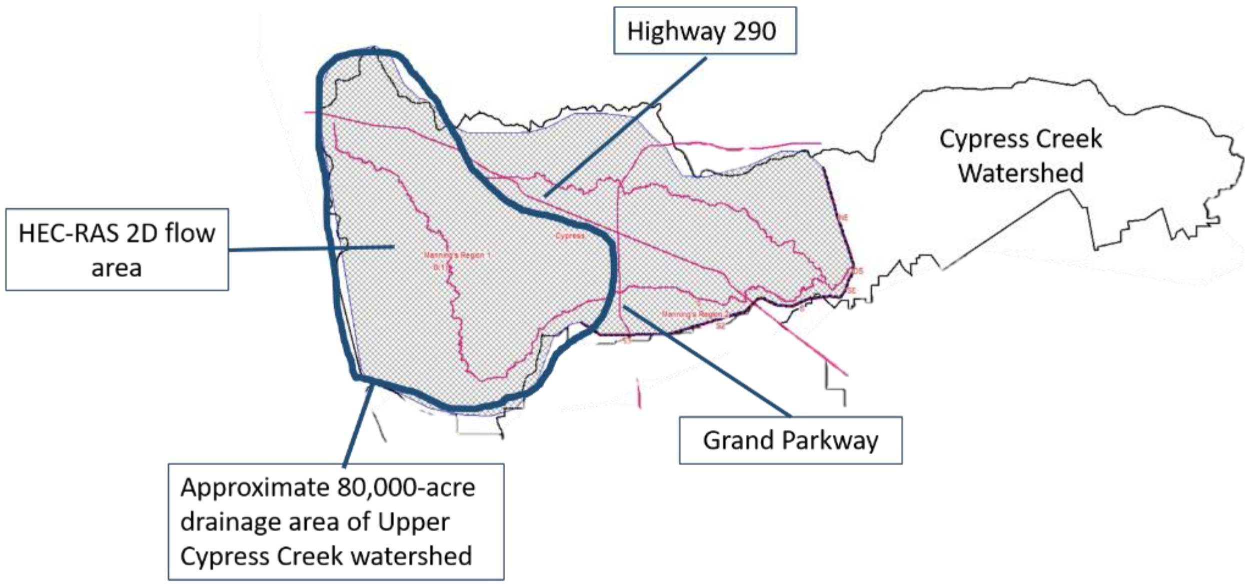


Figure 20. RAS 2D Flow Area for Retention Modeling of Depressions

The 80,000 acres were all within the bounds of the 100,000-acre study area discussed in this study, which ensured the total drainage area for Upper Cypress Creek was captured. In restricting the overflow to the watershed domain, all rainfall-runoff entering Upper Cypress Creek was directed downstream, where volume accumulation was evaluated just east of the Grand Parkway. The volume was evaluated using a profile line which extended across the width of the “outlet” for this area (including both overland and creek). The volume of flow accumulation was then subtracted from the total net precipitation volume (evaluated as inches of net rainfall x area of catchment, i.e. 80,000 acres), with the resulting difference being the amount of water retained in overland depressions. The model simulation duration was between 3 weeks to over a month, variant to storm size, to ensure all water within the creek had flowed out of the domain, and only overland stored runoff remained. Results of the total retained volume corresponding to each storm are summarized below in Table 5.

Table 5. Retention Capacity of Depressions in Undeveloped Land (including CPC property)

| STORM | VOLUME RETAINED (ACRE-FT/ACRE) |
|---|---|
| **10-YR** | 0.02 |
| **100-YR** | 0.09 |
| **500-YR** | 0.12 |

This evaluation includes all retention within the domain (including lakes, man-made detention etc.) and is not limited to natural depressions. However, it was observed that some prominent retention areas included facultative or emergent wetlands as categorized by the 2016 NLCD, and a lake on CPC property known as Warren Lake. The areas containing retained water ultimately coincided with the “depressions” isolated using ArcGIS processing. The total estimated retention volume for this area is about 7,000 acre-ft for the 100-year storm event (NOAA Atlas 14).

(Note: For more information on the qualitative findings and 2D hydraulic analysis on depression storage, please refer to the master’s thesis research published by M. Garner in January 2020 (Garner 2020)).

## 6.4 Further Analysis of Detention Benefits of Native Prairie Conversion

An additional analysis was performed using a rain-on-grid HEC-RAS 2D model, covering portions of upper Cypress Creek and Addicks watersheds, to estimate the detention benefits of converting current land cover to native prairie vegetation for the existing 20,000 acres of CPC lands (green shaded area), as well as an additional 10,000 acres of land in the vicinity of the CPC lands, for a total of 30,000 acres (brown shaded area), as shown in **Figure 21**.

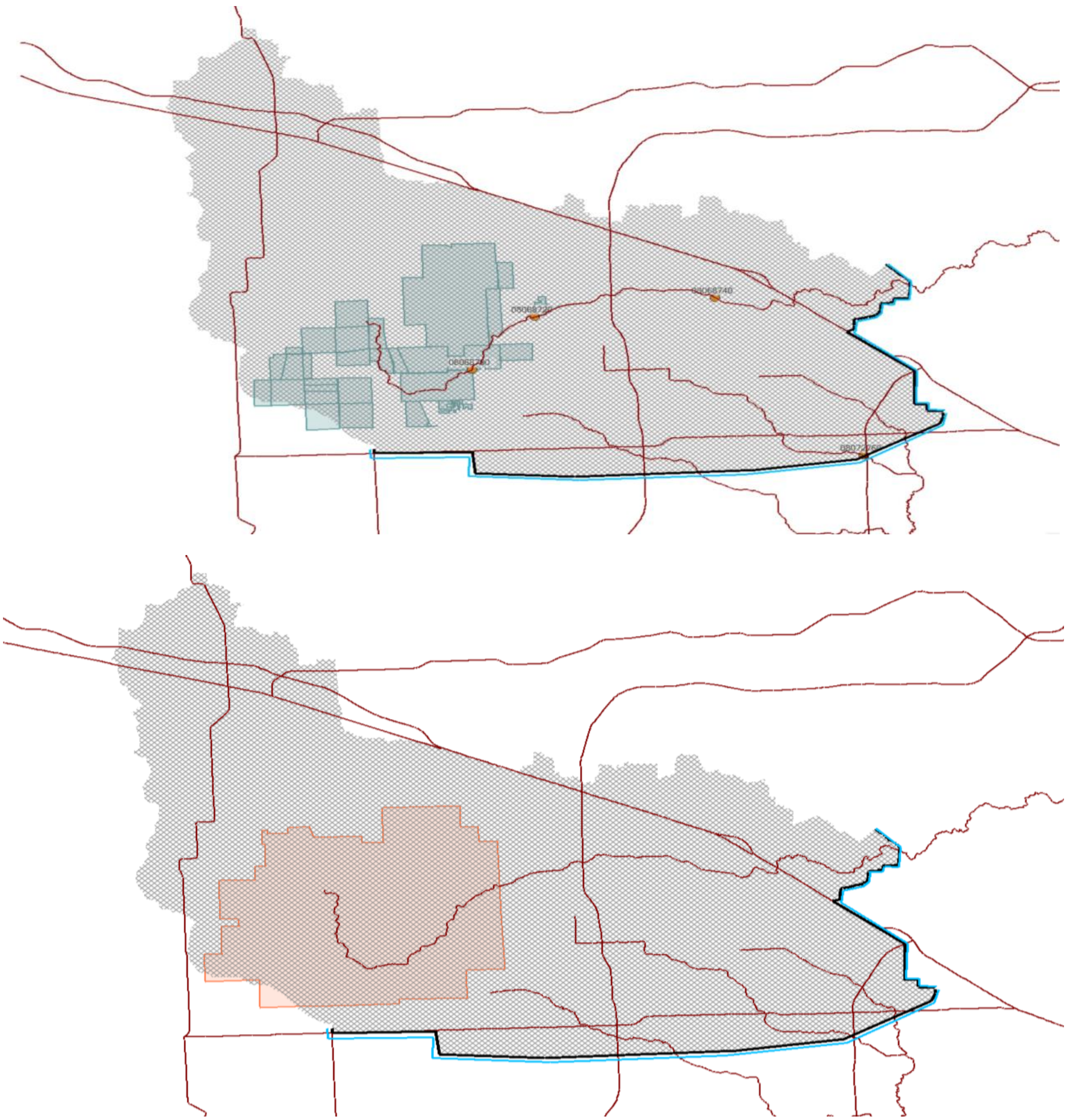

Figure 21. 20,000 acres (top) and 30,000 acres (bottom) of CPC Lands to be Converted.

The objective of this analysis was to estimate the detention benefits of converting these two sets of CPC land areas to native prairie on reducing Cypress Creek overflows into the Addicks watershed. The grey shaded area in Figure 21 above is the HEC-RAS 2D model domain used for this further analysis, covering upper Cypress Creek watershed upstream of Hwy 290, along with the upper portion of the Addicks Watershed.

The HEC-RAS 2D model was calibrated to the Tax Day 2016 and Harvey 2017 flood events, as these two events had significant Cypress Creek overflows int the Addicks Watershed. Details of this work are included in **Appendix F**.

The calibrated model was then run for various frequency storm events (Atlas 14) to estimate the overflows from upper Cypress Creek into the Addicks watershed for current/existing land use conditions, as shown in **Figure 22**. The area under the flow hydrographs shown in Figure 22 equates to the amount or volume of water that overflows. It appears that overflows into the Addicks watershed begin with the 10-year storm event. **Figure 23** shows the flow hydrographs for these various frequency storm events that continue along Cypress Creek downstream of the overflow area, as computed at the Katy Hockley gage, located upstream of Hwy 99.

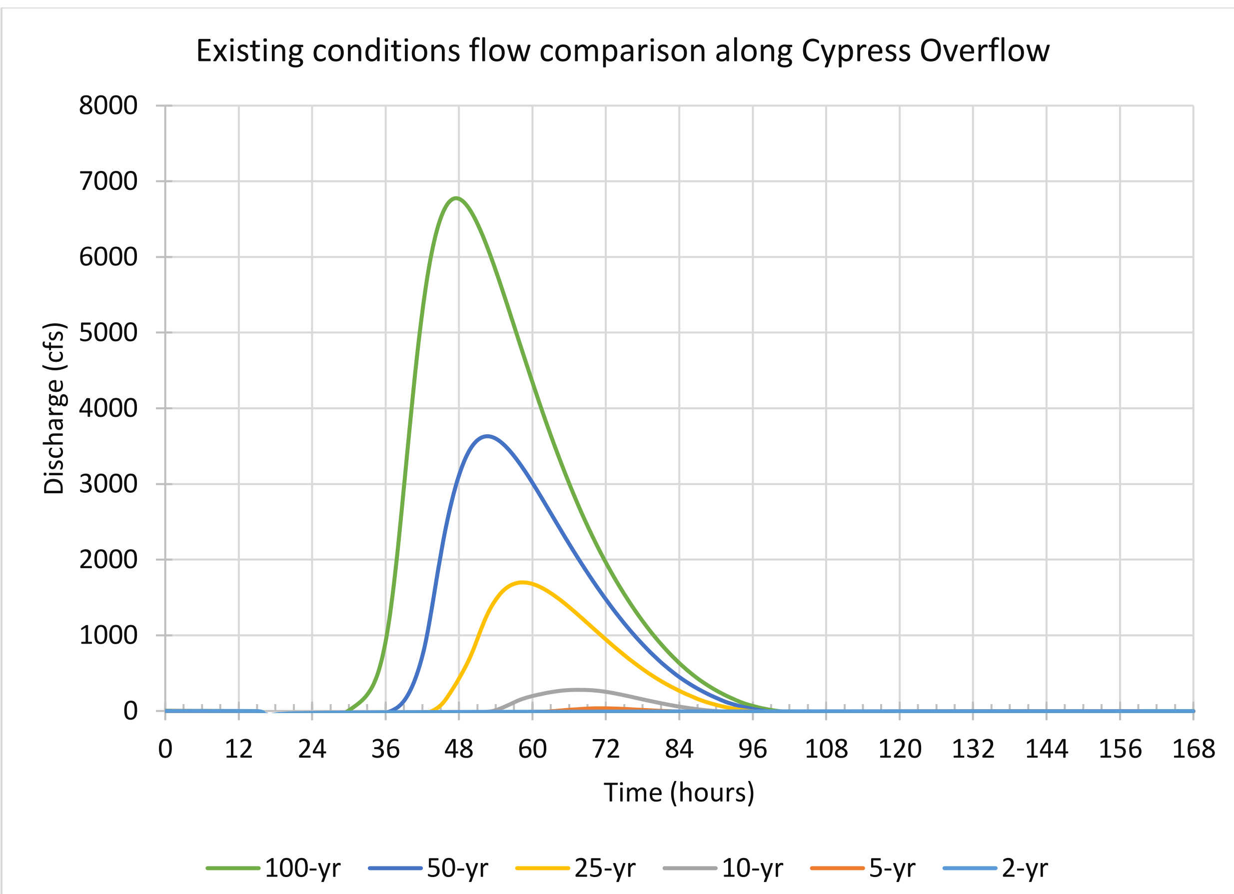


Figure 22. Various Frequency Flow Hydrographs Overflowing from Upper Cypress Creek

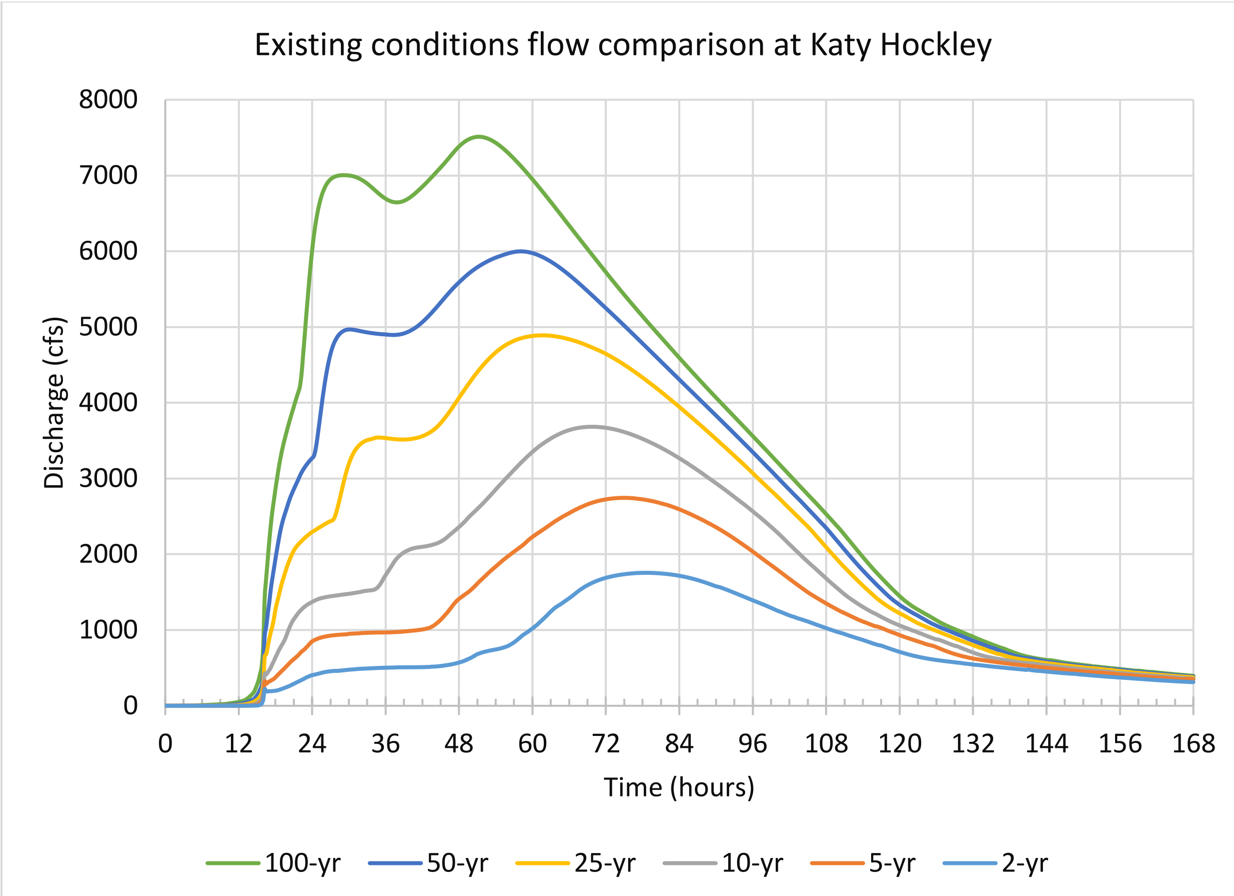


Figure 23. Various Frequency Flow Hydrographs along Cypress Creek at Katy Hockley Gage

This 2D model was then run for Scenario 1 in which the 30,000 acres, associated with the 20,000 acres of existing CPC lands along with 10,000 acres of expansion, are converted from the existing land cover to native prairie vegetation. A comparison of the resulting flow hydrographs for the 10- and 100-year storm events for the existing conditions and Scenario 1 (S1) are shown in **Figure 24** (for the overflows from cypress Creek into the Addicks watershed) and **Figure 25** (for the flows continuing downstream along Cypress Creek as computed at the Katy Hockley gage).

As can be seen in Figure 24, the conversion to native prairie results in reducing both the peak flow and runoff volume of water overflowing into the Addicks watershed, along with a delay in the timing of the runoff overflowing. This is expected due to the detention effects of the native prairie vegetation, as discussed earlier in this report. In addition, there was also a reduction in the peak flow and delay in the timing of the runoff continuing down along Cypress Creek, as shown in Figure 25. This 2D model analysis did not include the additional retention benefit of converting to native prairie vegetation, as discussed earlier in this report. With just analyzing the detention benefit of this conversion, it was estimated that for the 100-year event, the reduction in the runoff volume overflowing into the Addicks watershed was 0.4 ac-ft/acre of converted land.

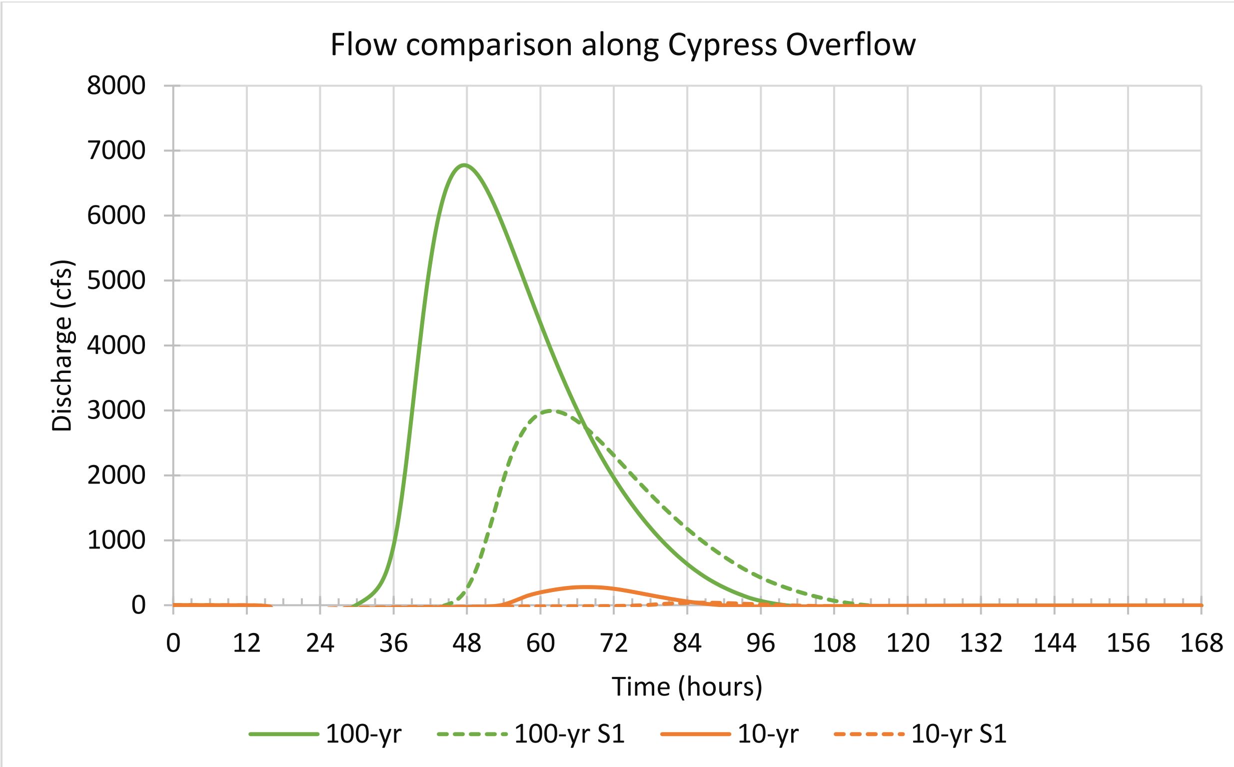


Figure 24. Comparison of Flows along Cypress Overflow for 10-yr and 100-yr Storm Events Between Existing Land Use Conditions and Scenario 1 (conversion to native prairie vegetation)

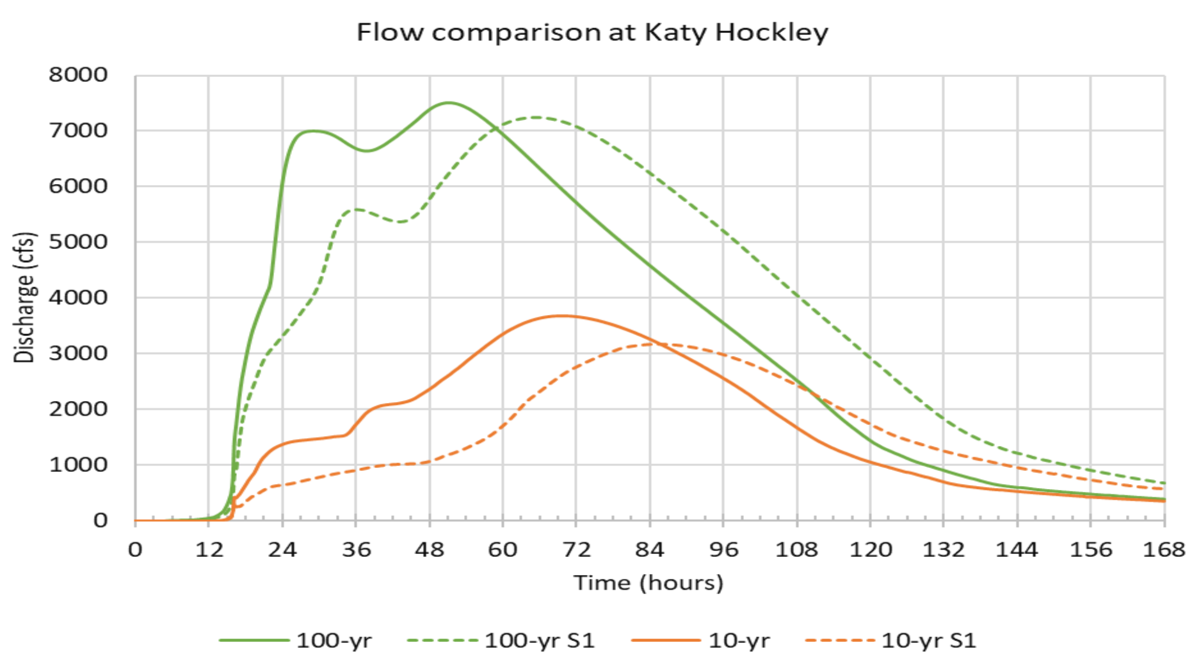


Figure 25. Comparison of Flows along Cypress Creek at Katy Hockley for 10-yr and 100-yr Storm Events Between Existing Land Use Conditions and Scenario 1 (conversion to native prairie vegetation)

## 7. Conclusions and Recommendations

This report has summarized the methodology applied in this study to begin to quantify the current detention and retention capacity of CPC land. As a result, this report additionally provides insight on the future influence of the land in flood mitigation with prairie restoration and expansion. This information is pertinent to the investigation of alternative flood mitigation options for Upper Cypress Creek in attempts to conserve and protect the current coastal prairie and provide enhanced or expanded prairie as an alternative to reservoirs and additional gray infrastructure. In conclusion, the main findings are summarized below along with recommendations for future investigation:

- The infiltration testing performed on CPC property resulted in an understanding that prairie vegetation enhances infiltration rates of top soil. Prairie vegetation creates higher infiltration rates as compared to the other vegetation types tested in this study.
- Additional studies have proven the enhanced infiltration created by prairie vegetative root structures to be consistent across a variety of soil types, including clay (Selbig and Balster 2010).
- Higher infiltration rates attributed to prairie vegetation were proven to reduce peak flow of rainfall runoff through hydrologic modeling performed in this study.
- The hydrologic land conversion portion of this study concluded that expanding and restoring tallgrass prairie would increase retained rainfall up to 0.2 acre-ft/acre of converted land. This was found to be largely controlled by top soil depth, however, so further investigation and surveys of soil depth within the CPC property is recommended.
- Overland vegetative roughness associated with native tallgrass prairie, along with the current state of CPC land, provides a substantial detention storage effect on rainfall-runoff, even for large volume (500-yr) storm events.
- A prairie expansion and restoration program has the potential to reduce peak flows of rainfall-runoff on average between 10-30% within upper Cypress Creek, due to overland roughness alone.
- Hydrologic modeling in this study further demonstrated that, currently, the CPC property provides about 0.5 ac-ft/ac of detention storage, thus meaning that to fully mitigate a fully developed area, there would need to be nearly double the amount of detention storage than the minimum required by HCFCD developmental standards (updated 2019 with reflection of Atlas 14 rainfall volumes).
- 2D hydraulic modeling provided qualitative insight into the depression storage potential in the Katy Prairie region, which is created through natural depressions in the topography known as prairie potholes. Further investigation should be pursued.
- 2D modeling showed the detention benefits of converting existing CPC lands to native prairie by reducing peak flows and runoff volume overflowing into the Addicks watershed and delaying the runoff overflowing and continuing down Cypress Creek.

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**A – Field Testing Results of Infiltration Rates**

**B – Hydrologic Modeling (HEC-HMS) Results and Infiltration**

**C – Hydrologic Modeling (Vflo®) Results and Infiltration**

**D – Hydraulic Modeling (HEC-RAS 1D/2D) Results**

**E – Hydrologic Modeling and Detention Storage**

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**Appendix A – Field Testing Results of Infiltration Rates**

**I. Introduction**

This infiltration study was conducted as part of a larger investigation into the effects of the Katy Prairie on flooding in the Cypress Creek and/or Addicks watersheds. The purpose of the infiltration study was to obtain measured hydraulic conductivity (K) values (infiltration rates in inches per hour) for different land cover/vegetation types throughout the area in and around the lands conserved by the Coastal Prairie Conservancy (CPC). Fifteen (15) sites were selected for testing the various selected land cover/vegetation types. The results from these tests were then compared against literature K values for various soil types to determine the effect of land cover and vegetation on hydraulic conductivity. These values are then intended to be used to refine the hydrologic modeling of the watersheds throughout the CPC area.

II. **Methods**

The tests were conducted using three Decagon Dualhead Infiltrometers at each site. The tests were conducted according to the manufacturer's directions. The vegetation directly above each insertion ring was cut back to ground level with shears. At each selected site one test was run on each device in close proximity to each other, for a total of three tests per site. The devices were placed about 30 feet away from each other while the tests were running. The tests were run on the suggested settings for a soil type of dry loamy sand, with an insertion depth of 5 cm. The sites were selected by Applied Ecological Services (AES) as representative of the type of land use/vegetation in the area. Each site was given a site name and assigned a number. Of the 15 sites, 13 were directly in or on plots associated with CPC property. The remaining 2 tests were conducted on open space in developed areas. Testing occurred between April 10, 2017 and May 19, 2017. A map of the 15 tested infiltration sites is shown below (Fig A-1).

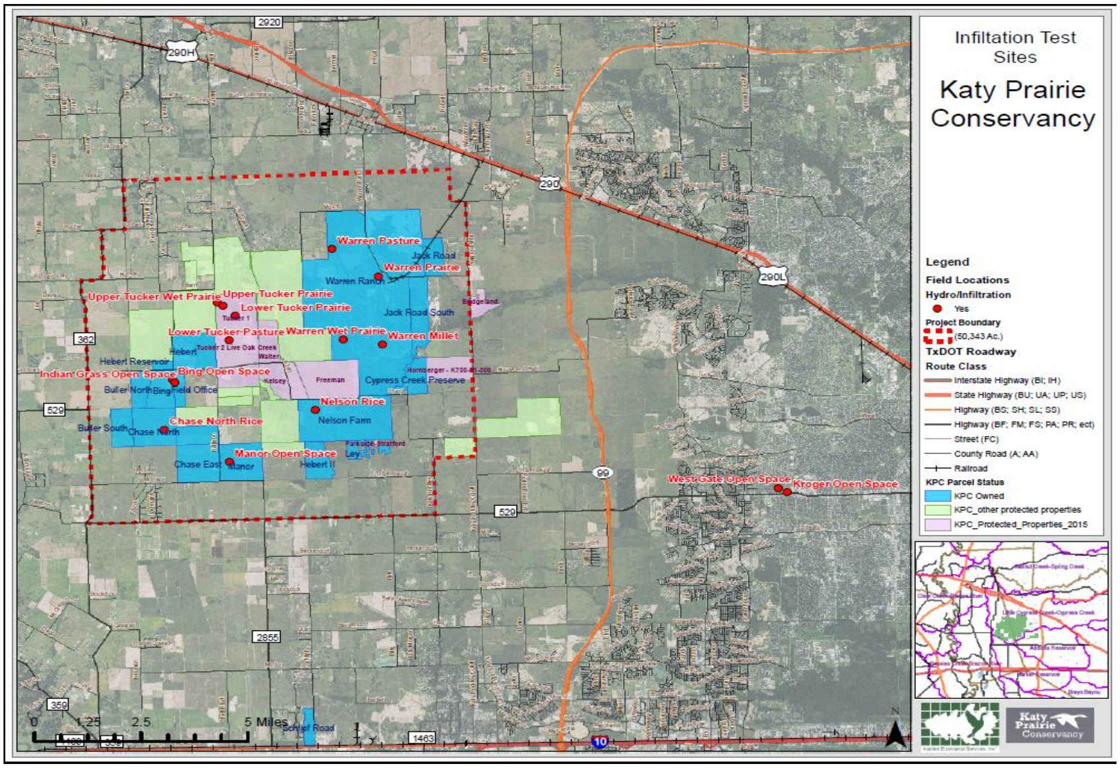



**Figure A-1: Location map of the 15 selected infiltration test sites**

After the tests were run, the three resulting K values for each site were averaged using both geometric and arithmetic means. These K values represented both the soil type as well as the land cover/vegetation type at each site. In order to isolate the K value associated with only the land cover/vegetation type, K values for the different soil types found at each site were needed. Soil data for the region was obtained through the United States Geological Survey (USGS). The average K values determined from the tests for each site were then compared to the literature K values ($K_{soil}$) for the specific soil type of each site (Rawls et al). The literature value from each site was then subtracted from the tested K value. The remaining infiltration K value ($K_{veg}$) was attributed to the particular vegetation observed at each site. If the literature K value was higher than the tested K value, the vegetation was assumed to have no effect on the infiltration rate and the $K_{veg}$ value was set to 0. Any extreme values from infiltration tests were not included when subtracting the $K_{soil}$ from the arithmetic mean of tested K values. All test results were included when subtracting from the average K value using the geometric mean.

There were a wide range of K values obtained during the testing at particular sites. For example, one site had the three reported K values ranging from about 1 to over 16 inches per hour. One possible source of error for the test includes subsurface features, such as gopher tunnels or salt deposits, which might impact the infiltration testing. Another possible error source is in the listed soil type for that test site. Certain test sites, such as Site 6: West Gate Open Space, occurred on developed land. During development of the site, soil may have been brought in to the site as fill material that was different than the soil type reported for that area, causing an error when calculating $K_{veg}$. Similarly, if the listed USGS soil type under a site is incorrect, $K_{veg}$ will have been calculated using the wrong soil type.

## III. Results

A table of infiltration results can be found below. The results for the $K_{veg}$ calculations are also tabulated below.

| Site Number | Type | Name | K1 | K2 | K3 | GeoMean | ArithMean | KUnits |
|---|---|---|---|---|---|---|---|---|
| 8 | Wet Prairie | Warren Wet Prairie | 1.06E-03 | 3.90E-04 | 9.47E-04 | 7.32E-04 | 7.99E-04 | cm/s |
| 15 | Row Crop | Warren Millet | error | 1.27E-03 | 7.36E-04 | 9.67E-04 | 1.00E-03 | cm/s |
| 3 | Pasture | Bing Open Space | 1.83E-04 | 2.80E-04 | 7.24E-04 | 3.34E-04 | 3.96E-04 | cm/s |
| 7 | Open Space | Indian Grass Open Space | 0.000435 | 0.00141 | 2.59E-04 | 5.42E-04 | 7.01E-04 | cm/s |
| 2 | Pasture | Manor Open Space | 1.76E-04 | 1.73E-04 | 1.26E-03 | 3.37E-04 | 5.36E-04 | cm/s |
| 10 | Rice | Nelson Rice | 2.64E-04 | 2.58E-04 | 8.43E-04 | 3.86E-04 | 4.55E-04 | cm/s |
| 11 | Rice | Chase North Rice | 1.73E-04 | 6.17E-04 | 3.44E-04 | 3.32E-04 | 3.78E-04 | cm/s |
| 12 | Pasture | Warren Pasture | 1.02E-03 | 4.80E-03 | 1.30E-03 | 1.85E-03 | 2.37E-03 | cm/s |
| 13 | Prairie | Warren Prairie | 1.14E-02 | 8.95E-04 | 6.14E-03 | 3.97E-03 | 6.15E-03 | cm/s |
| 5 | Open Space | Kroger Open Space | 2.12E-04 | 2.04E-03 | 2.06E-04 | 4.47E-04 | 8.19E-04 | cm/s |
| 6 | Open Space | West Gate Open Space | error | 2.27E-03 | 1.67E-03 | 1.95E-03 | 1.97E-03 | cm/s |
| 1 | Prairie | Upper Tucker Prairie | 2.96E-03 | 4.61E-03 | 3.00E-03 | 3.45E-03 | 3.52E-03 | cm/s |
| 14 | Wet Prairie | Upper Tucker Wet Prairie | 6.16E-04 | 1.91E-03 | 6.16E-04 | 8.98E-04 | 1.05E-03 | cm/s |
| 4 | Prairie | Lower Tucker Prairie | 1.91E-03 | 4.11E-03 | 4.06E-03 | 3.17E-03 | 3.36E-03 | cm/s |
| 9 | Pasture | Lower Tucker Pasture | 4.21E-03 | 9.15E-03 | 6.78E-03 | 6.39E-03 | 6.71E-03 | cm/s |

**Table A-1. Infiltration testing results. (Note: The test number corresponds to the order in which testing in the device began, not the device itself. This means that the K1 column contains results from all three devices in various rows.)**

| **Site Number** | **Name** | **Type** | **Soil Type** | **Ksoil** (in/hr) | **Kveg,geo** (in/hr) | **Kveg,arith** (in/hr) |
|---|---|---|---|---|---|---|
| 5 | Kroger Open Space | Open Space | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 6 | West Gate Open Space | Open Space | Sandy Loam | 0.429 | **2.330** | **1.938** |
| 7 | Indian Grass Open Space | Open Space | Sandy Loam | 0.429 | **0.338** | **0.063** |
| 2 | Manor Open Space | Pasture | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 3 | Bing Open Space | Pasture | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 9 | Lower Tucker Pasture | Pasture | Loamy Sand | 1.177 | **7.883** | **8.338** |
| 12 | Warren Pasture | Pasture | Sandy Loam | 0.429 | **2.197** | **1.215** |
| 1 | Upper Tucker Prairie | Prairie | Sandy Loam | 0.429 | **4.456** | **3.794** |
| 4 | Lower Tucker Prairie | Prairie | Loam | 0.134 | **4.360** | **4.097** |
| 13 | Warren Prairie | Prairie | Loam | 0.134 | **5.495** | **8.576** |
| 10 | Nelson Rice | Rice | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 11 | Chase North Rice | Rice | Sandy Loam | 0.429 | **0.000** | **0.000** |
| 15 | Warren Millet | Row Crop | Sandy Loam | 0.429 | **0.941** | **0.992** |
| 8 | Warren Wet Prairie | Wet Prairie | Loam | 0.134 | **0.903** | **1.288** |
| 14 | Upper Tucker Wet Prairie | Wet Prairie | Sandy Loam | 0.429 | **0.844** | **0.444** |

**Table A-2. Average Infiltration rates attributed to the vegetation type at each of the 15 test sites.**

## IV. Discussion

The above results provide valuable information when assessing runoff potential from rainfall events. Areas with high infiltration rates are able to retain more water and reduce total volume of runoff when compared to areas with low infiltration rates. After running the infiltration tests at various sites we were able to see the possible effect of land cover/vegetation on infiltration rates. Some land cover types, such as open space, have little to no effect on infiltration rates beyond that associated with the underlying soil type. Other land-cover types, on the other hand, seem to play a large role in effecting infiltration rates. “Prairie” especially is seen to have a large effect on infiltration rates. This indicates that having an abundant of prairie land and restoring other land cover types to imitate “prairie” could lead to a reduction in downstream flooding.

**Appendix B – Hydrologic Modeling (HEC-HMS) Results**

## HCFCD Hydrologic Modeling – HEC-HMS (M3 System)

**Overview**

The hydrologic tool used by HCFCD is the Hydrologic Modeling System (HEC-HMS), developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. HEC-HMS was designed to simulate the complete hydrologic processes of various watershed systems. The tool allows hydrologic analysis procedures such as infiltration, rainfall-runoff transformations, and hydrologic routing. HEC-HMS simulation results are stored in a data management system called HEC-DSS (Data Storage System), and can be easily linked to a hydraulic model, HEC-RAS, or other HEC-developed software.

HCFCD has made available all hydrologic and hydraulic models (i.e., HEC-HMS and HEC-RAS) for all watersheds within Harris County through its Model and Map Management, or the M3, system (http://www.m3models.org/). The models for Cypress Creek were downloaded and used as reference in this project.

### May 2016 and Tax Day 2016 Storms

To evaluate the performances of HCFCD's M3 HEC-HMS model in recent storm events, the May 2016 storm and the April (Tax Day) 2016 storm were simulated. The following figures show the comparison between HEC-HMS modeled results vs observed data at three USGS gage locations for the two storms.

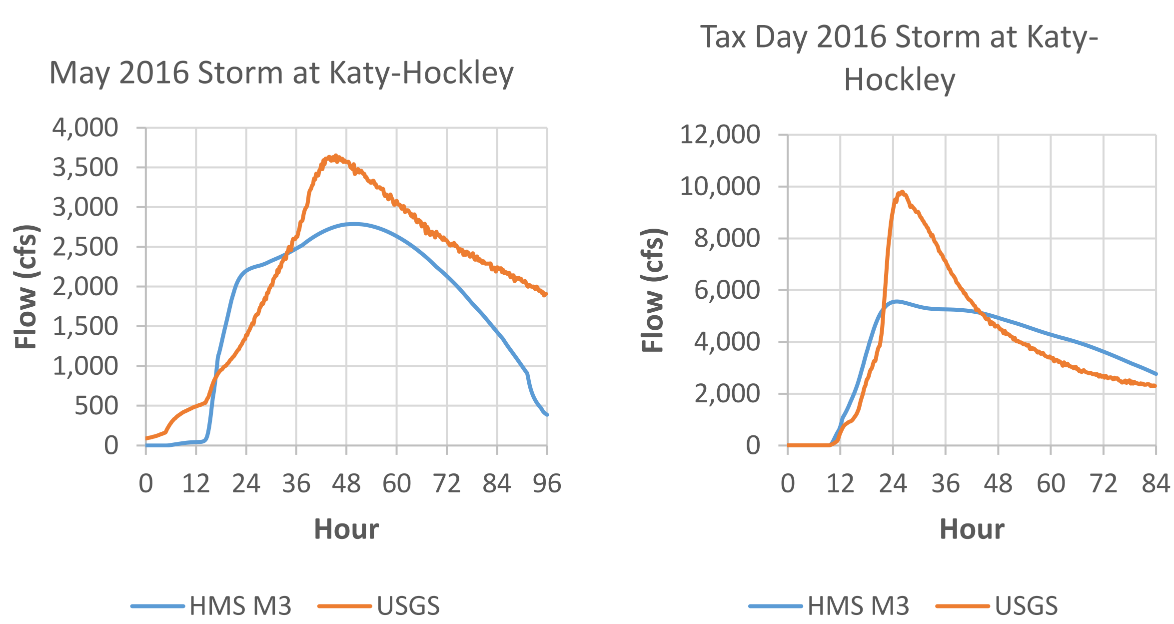



**Figure B-1. Flow comparison between HMS and Gage data at Katy-Hockley for April and May 2016**

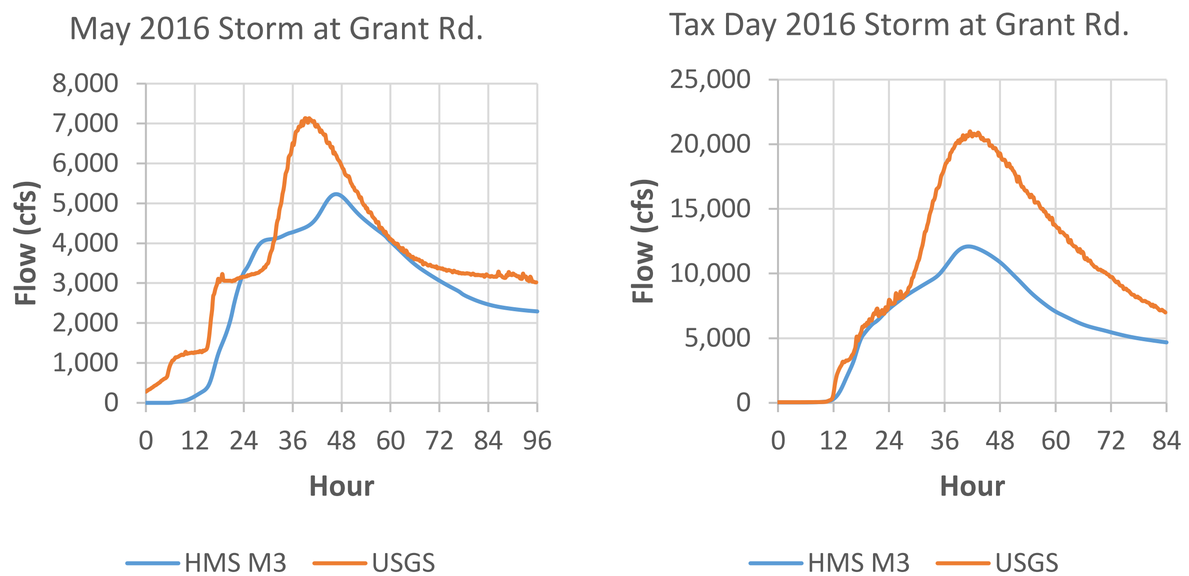



**Figure B-2. Flow comparison between HMS and Gage data at Grant Road for April and May 2016**

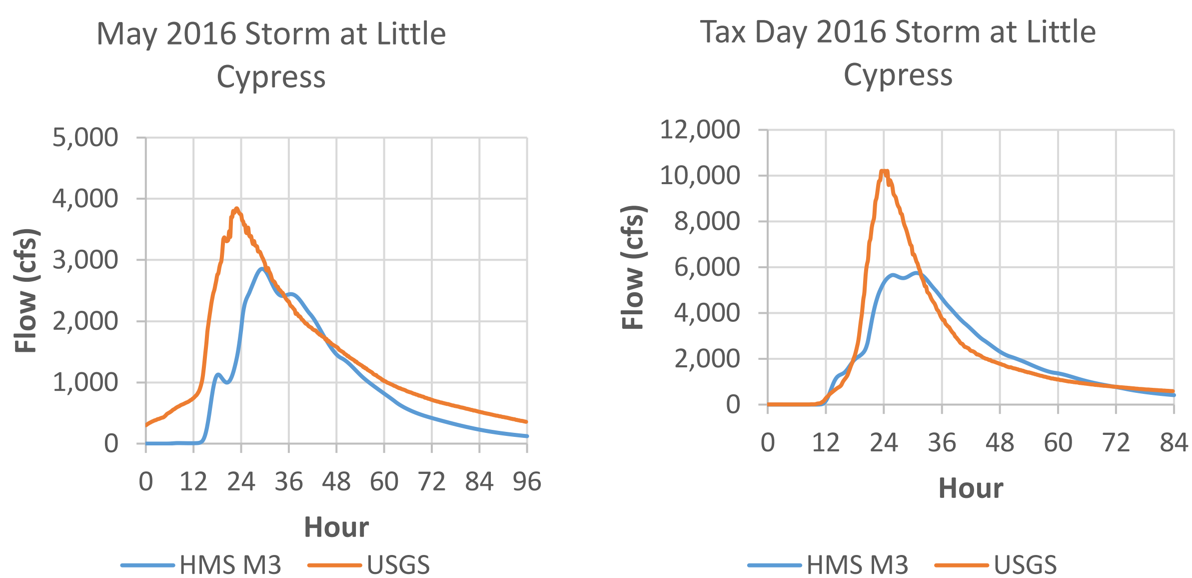



**Figure B-3. Flow comparison between HMS and Gage data at Little Cypress Creek for April and May 2016**

Overall, the modeled M3 results did not match very well with the observed gage data, both in peak flows and volume. This was especially apparent for the Tax Day 2016 results, a storm event which was known to have substantial overflows across the Cypress-Addicks watershed divide.

## Appendix C – Hydrologic Modeling (Vflo®) Results (Infiltration)

### Overview

In order to represent the spatially-varying soil and vegetation characteristics of Upper Cypress Creek and the Katy Prairie, it was necessary to develop a distributed hydrologic model, which relies on grid cell format to represent model parameters. The modeling software Vflo® ® was chosen, since it has been successfully applied to numerous watersheds across the Houston region. Input data for the Vflo®® model of Cypress Creek includes topographic, land use, land cover, and soil type information. Once developed, the model was calibrated to two recent storm events. Connections from the hydrologic model Vflo®® to the hydraulic model HEC-RAS were created to allow overland flows to be routed through the channel and through the overflow region. Finally, infiltration analysis was conducted by modeling various prairie conversion scenarios under varying rainfall magnitude and soil depth (storage capacity). The following sections describe the methods used for data collection and pre-processing, model set-up and calibration, and connecting model output to HEC-RAS.

### Hydrologic Model Theory and Set-up

Vflo® is a physics-based, fully-distributed hydrologic model developed by Dr. Baxter Vieux that solves conservation of mass and momentum equations using a finite-element approach in order to model the rainfall-runoff process (Vieux & Vieux, 2002). The watershed domain is represented in a grid-cell format, and each cell contains parameters that account for elevation, soil type, and land cover. Grid cells can either be classified as overland or channel cells, and rainfall-runoff calculations are conducted at each grid cell. Water is routed between overland cells via the Kinematic Wave Analogy (KWA), and Modified Puls routing was selected as the channel routing method for this study due to the relatively mild slope of the watershed. A full description of the Vflo® model formulation and derivation of the KWA is documented in Vieux & Vieux (2002). Infiltration is modeled using the Green and Ampt Equation, which depends on soil properties of hydraulic conductivity, wetting front capillary pressure head, and effective porosity.

While traditional methods to model 100-year floodplains have utilized lumped hydrologic models, such as HEC-HMS, distributed models have the ability to represent spatially-diverse soil and land cover characteristics, and thus can provide a more accurate representation of the physical parameters of the watershed. Vflo® models have been successfully developed and utilized to model the overland hydrologic response in numerous watersheds in the Houston region, e.g. Doubleday et al (2014). Since distributed hydrologic models are able to represent spatially-varying hydrologic parameters, Vflo® is a powerful tool for modeling the cumulative impacts of land cover changes. Previous studies have demonstrated Vflo®'s ability to evaluate LID features, development scenarios, and watershed evolution through time (Juan et al, Doubleday et al, Fang et al).

The Vflo® model was set up to represent the entire Cypress Creek watershed, and 300-foot grid cells were specified. This corresponds to approximately 95,000 grid cells within the model domain. Channel cells are designated based on a shapefile of existing channels (from HCFCD) as well as a flow accumulation threshold. Figure C-1 shows the model layers and model interface.

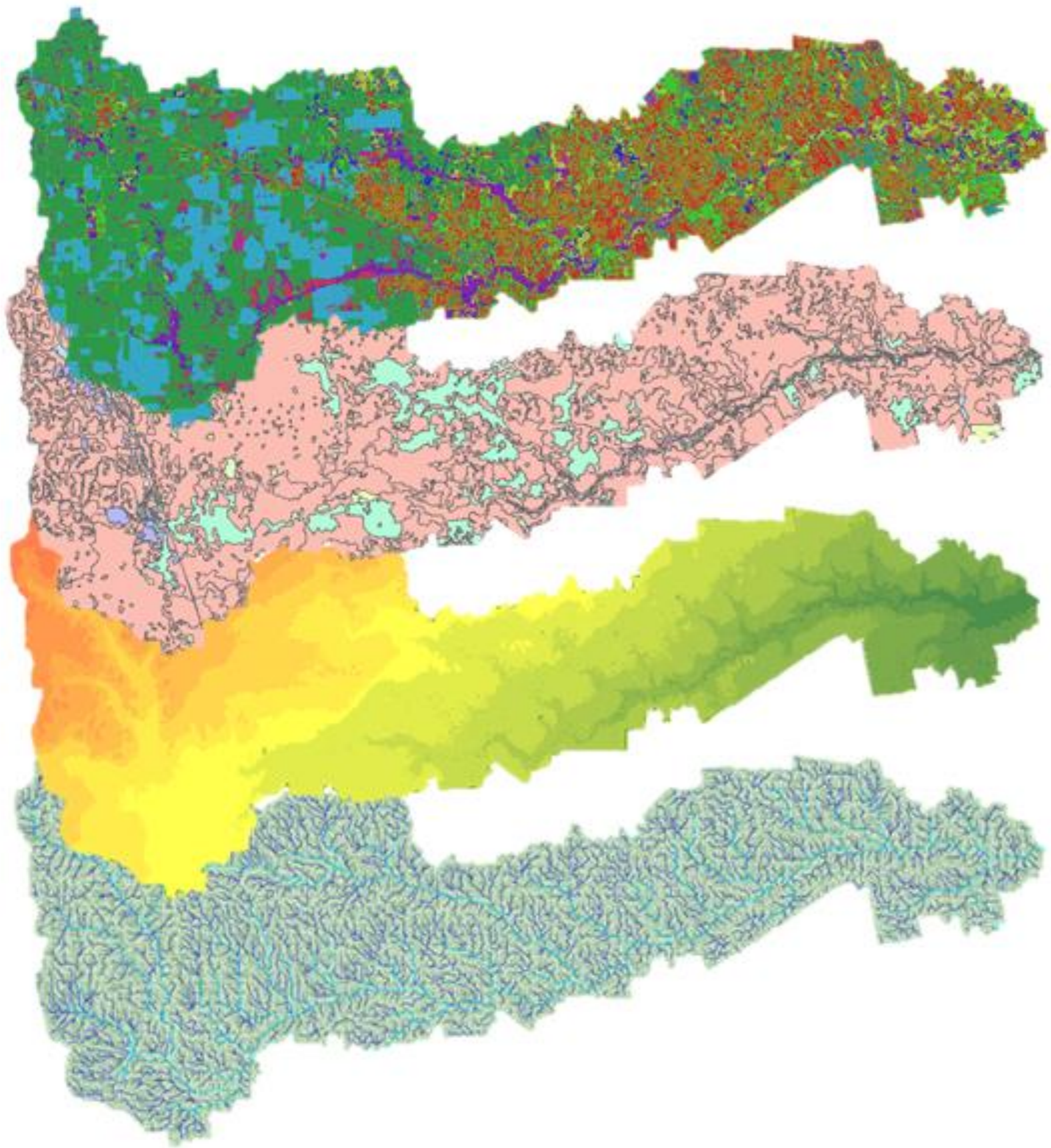


**Figure C-1. Vflo® model layers of input data (land cover, soil type, topography and channels)**

**Data Collection and Pre-processing**

The Vflo®® model set up relies on high-quality input data of elevation, land use, land cover, and soil type. Elevation information is obtained from USGS National Elevation Database. This data is obtained as a seamless 10m resolution raster, deriving from Lidar point cloud information. The predominant source date for this raster is 2008 Lidar (from Harris County), but the small portion of the study area within Waller County may have a newer source date. The USGS DEM product integrates many different Lidar datasets to produce a seamless elevation dataset, making it preferable to manual download and mosaicking of individual county datasets. Figure C-2 shows the USGS DEM for the Cypress Creek watershed.

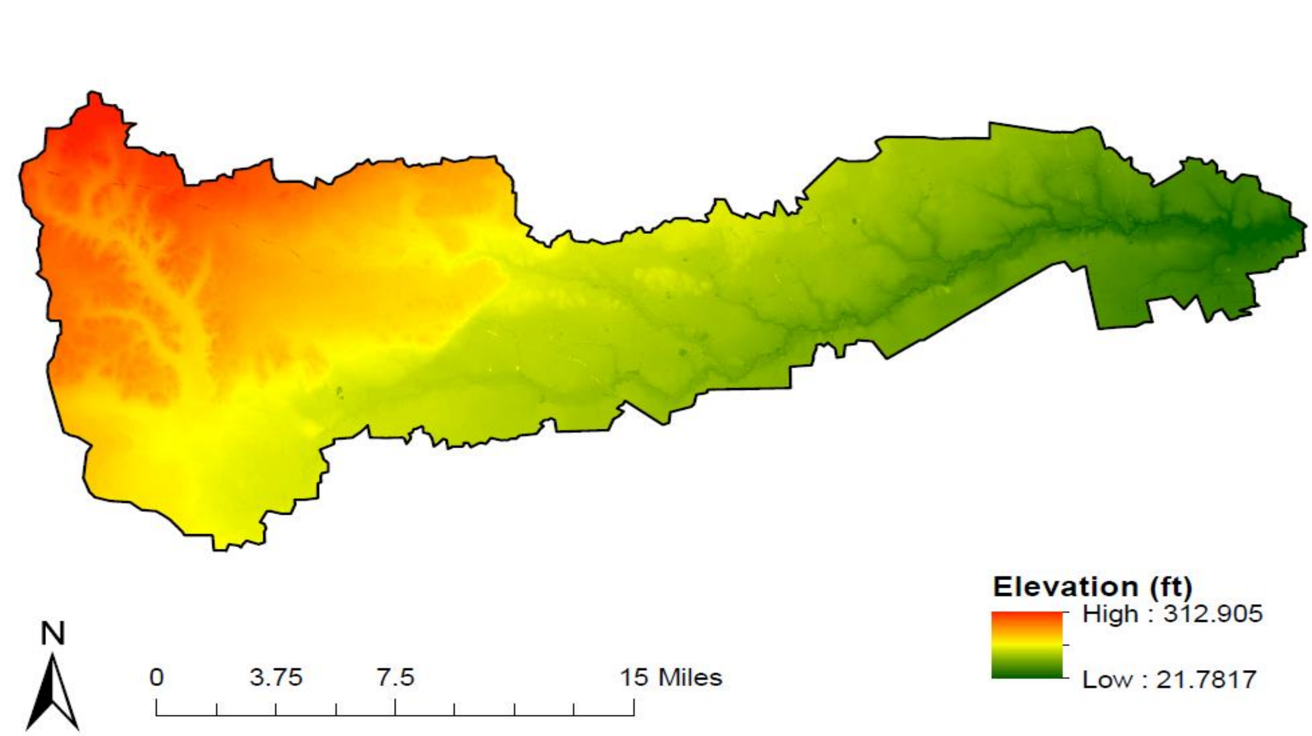



**Figure C-2. Topography (DEM) of the Cypress Creek Watershed**

Land use data is obtained from the USGS National Land Cover Database (NLCD). The most recent release of the NLCD data is from 2011, and this land use serves to represent the "current conditions" of the model (Figure C-3).

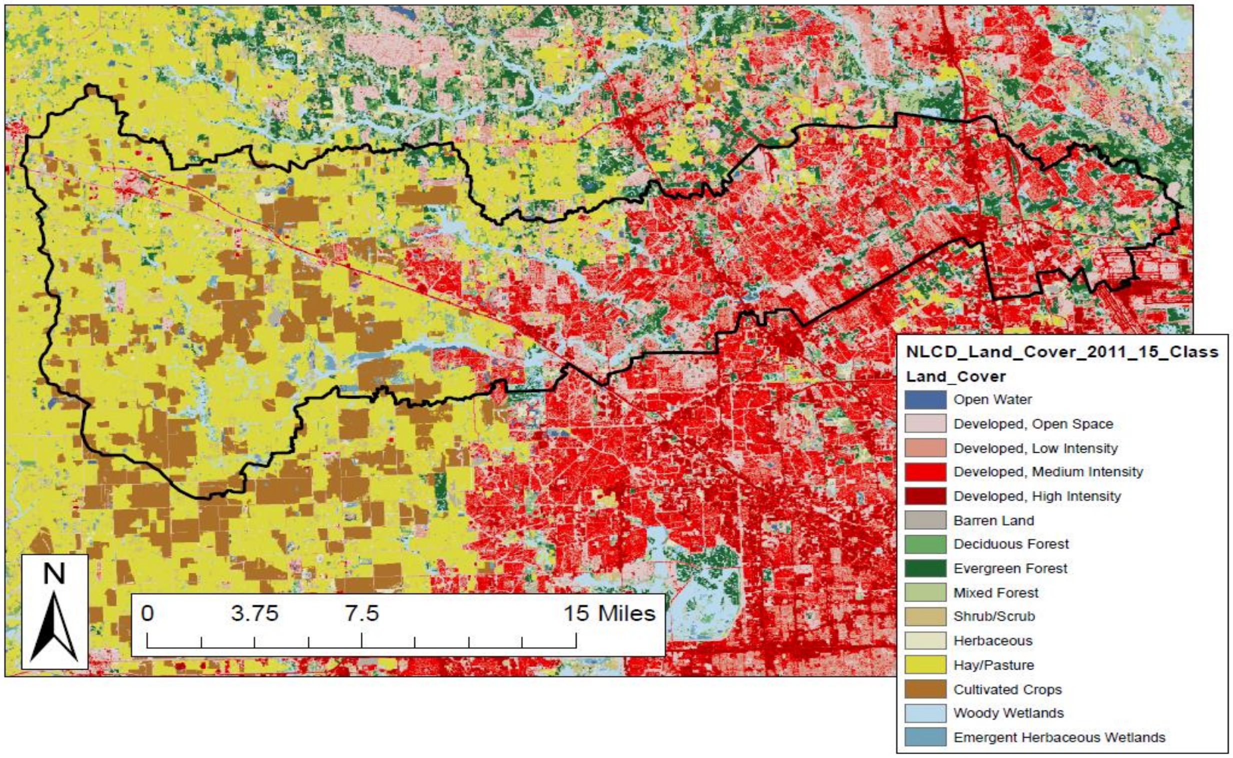



**Figure C-3. 2011 Land Cover Types for the Cypress Creek Watershed (from NLCD)**

Updated land cover information was also obtained from AES, with more detailed information about vegetative cover within the Upper Cypress Creek study area. This updated information was compared with the NLCD 2011 data to confirm agreement between the two sources. The Vflo®® model represents land use/cover (LULC) information by using two parameters: a Manning's roughness value and an impervious percentage. Manning's roughness is a parameter that accounts for frictional losses between overland flow and the ground surface. Concrete or developed areas generally have lower roughness, resulting in less frictional losses, and consequently greater speed of overland flow. On the other hand, natural vegetation has a high roughness value, which slows down overland flow and attenuates the peak flow. Impervious percentage accounts for the fraction of the area that is covered with impervious surface, and thus unable to be used for infiltration of rainfall. Again, areas of higher development have greater impervious percentage, and thus increase the volume of overland runoff compared to natural areas. For each land use category in the NLCD data, roughness values are derived using Kalyanapu (2010). Table C-1 shows the roughness values utilized in the model, and Figure C-4 shows roughness across the watershed.

**Table C-1. Overland Manning's Roughness Values for Different Land Cover Types**

| Land Cover | Description | Manning's n |
|---|---|---|
| 21 | Developed, open space | 0.0404 |
| 22 | Developed, low intensity | 0.0678 |
| 23 | Developed, medium intensity | 0.0678 |
| 24 | Developed, high intensity | 0.0404 |
| 31 | Barren land | 0.0113 |
| 41 | Deciduous forest | 0.36 |
| 42 | Evergreen forest | 0.32 |
| 43 | Mixed forest | 0.40 |
| 52 | Shrub/scrub | 0.40 |
| 71 | Grassland/herbaceous | 0.368 |
| 81 | Pasture/Hay | 0.325 |
| 90 | Woody wetlands | 0.086 |
| 95 | Emergent herbaceous wetlands | 0.1825 |

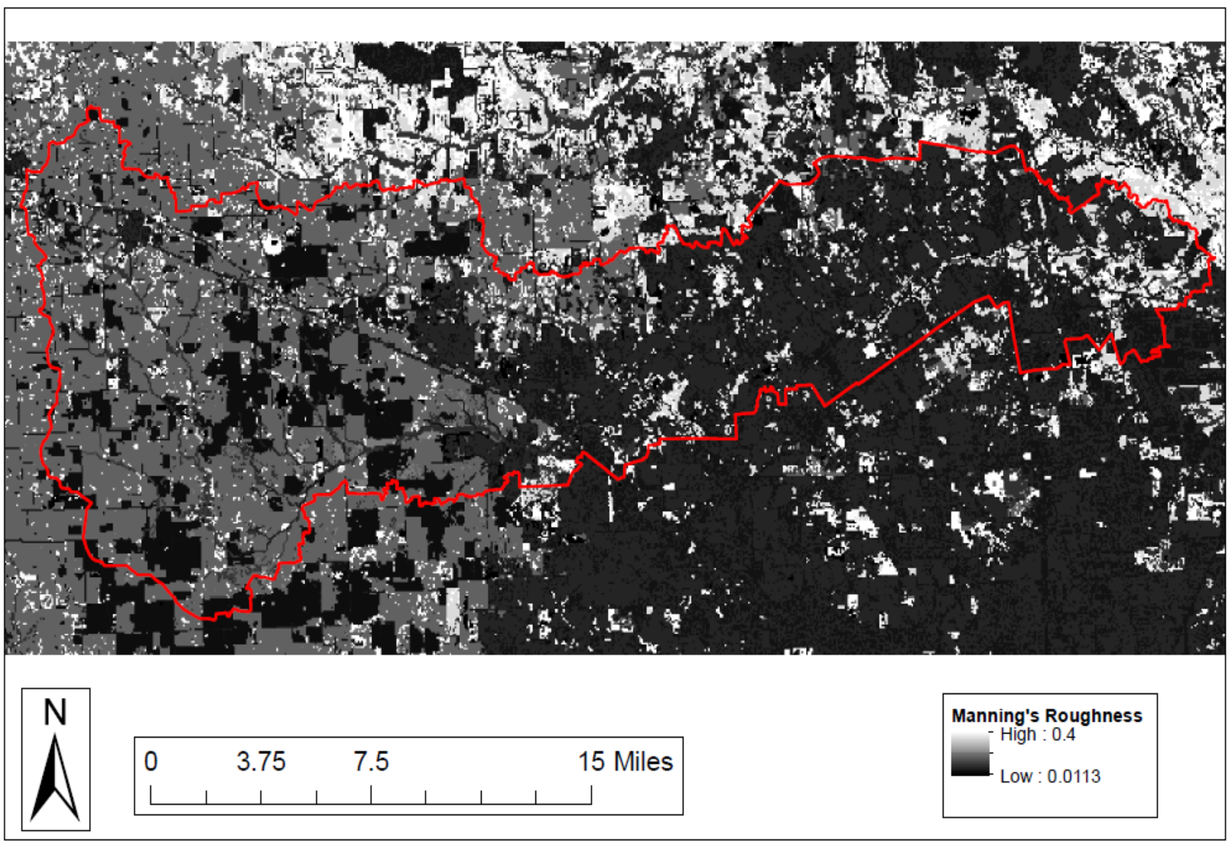



**Figure C-4. Overland Manning's Roughness Values across the Cypress Creek Watershed**

Impervious percent values are obtained from a second 2011 NLCD dataset, which converts each land use category to a corresponding impervious percent estimate (Figure C-5).

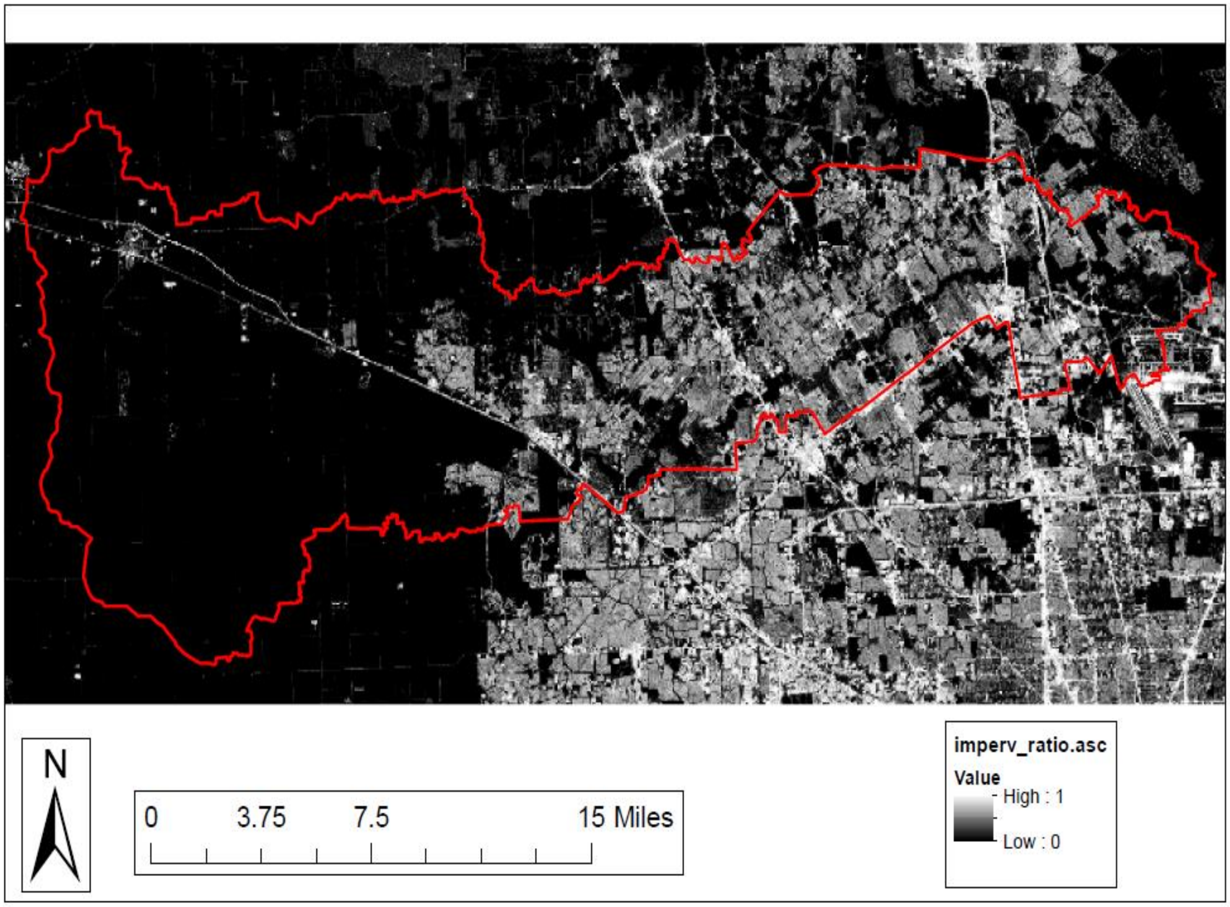



**Figure C-5.  Percent Imperviousness for Cypress Creek Watershed**

Soil-type data was obtained from the Texas Natural Resources Information System and compiled by the Natural Resource Conservation Service of the USDA. Infiltration is modeled using the Green & Ampt equation, which requires parameters of hydraulic conductivity, porosity, and wetting front capillary pressure. Additionally, the Vflo®® model allows soil depth information as a measure of maximum soil storage capacity. These values were derived for each soil type according to Rawls et al (1983). Figure C-6 shows the hydraulic conductivity derived by soil type for Upper Cypress Creek, and Figure C-7 shows the soil depth.

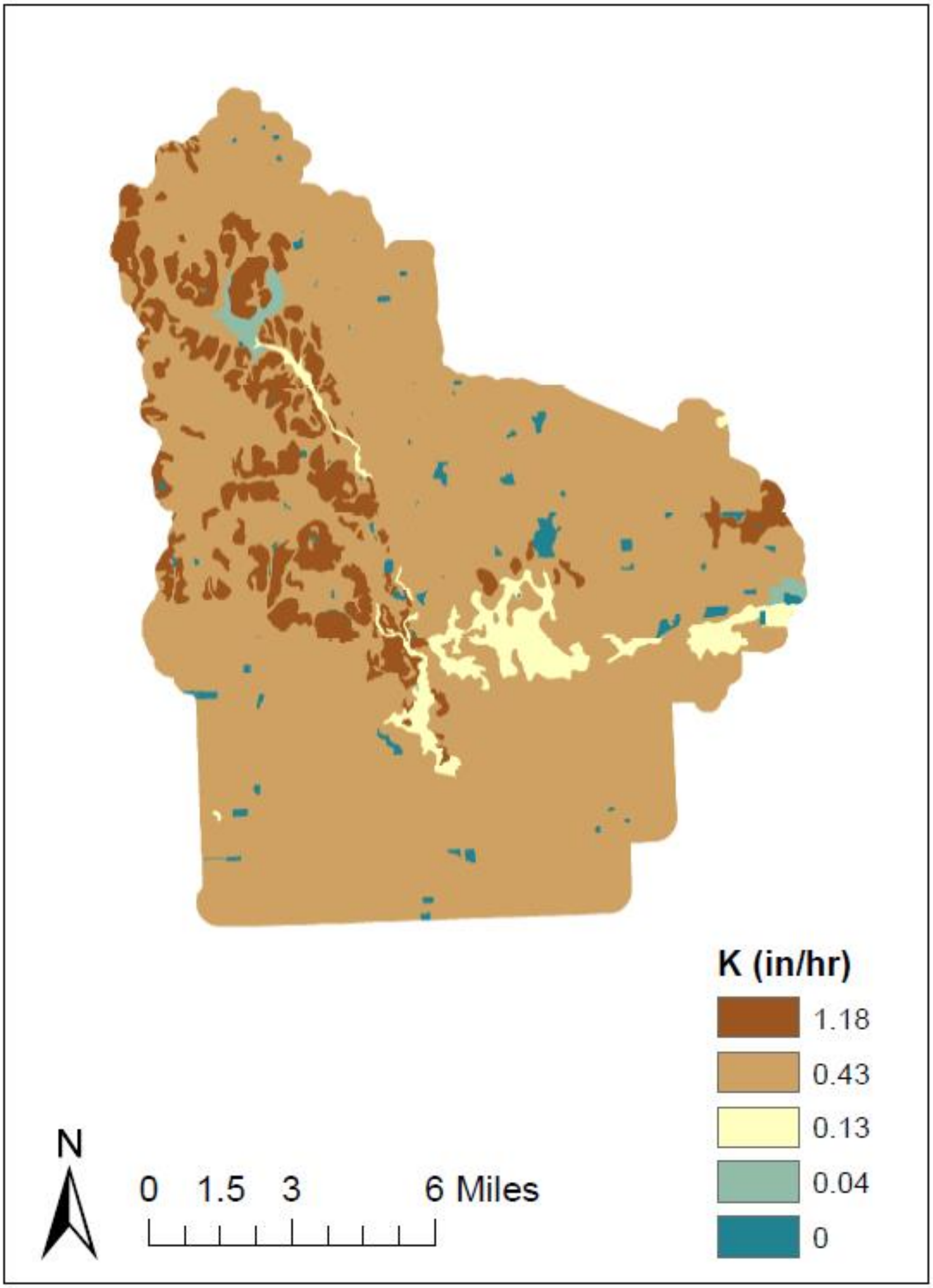



**Figure C-6. Ksoil Values for the Different Soil Types in Upper Cypress Creek Watershed**

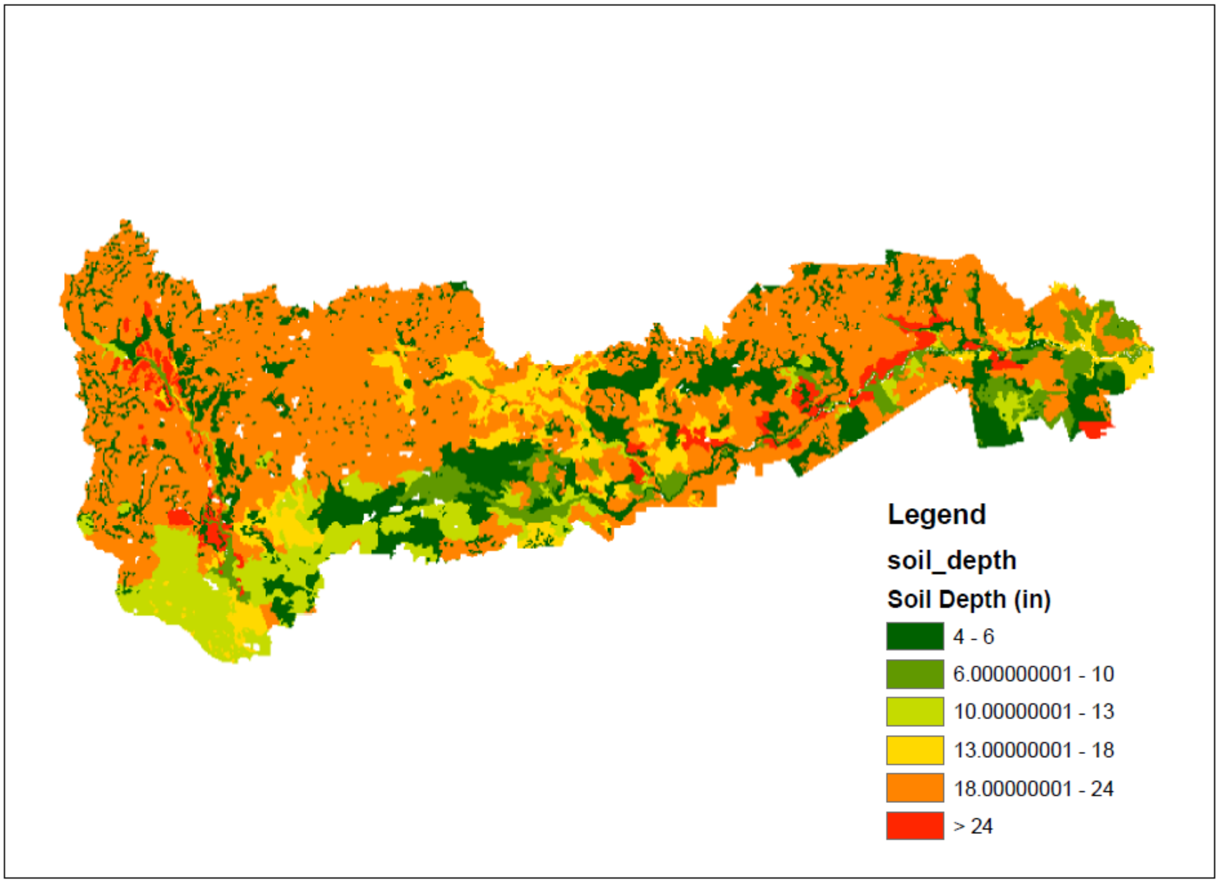



**Figure C-7. Soil Depths for the Different Soil Types in the Cypress Creek Watershed**

Based on the infiltration testing and subsequent analysis (see Infiltration Testing Methods, Appendix A), updated hydraulic conductivity information based on vegetated cover type was added as input to the model. This data was merged with the existing hydraulic conductivity dataset based on soil type to derive a total hydraulic conductivity, K in inches/hour, and is shown in Figure C-8.

**Hydrologic Model Calibration**

The Vflo®® model was calibrated using two recent high-intensity precipitation events. The first event was the Tax Day storm of April 2016, which roughly corresponds to between a 100-year and 500-year magnitude rain event. The second storm was May 2016, which corresponds to roughly a 10-year rain event. These storms were chosen because they represent a range of recent storm magnitudes, and ensure that the model is calibrated for multiple storm intensities. NEXRAD Level II radar rainfall was obtained from each storm event, and in both cases the radar rainfall was calibrated to local rain gauges. For the Tax Day event, radar was available in 1km cell resolution, while for the May event radar rainfall was obtained at 4km resolution. As demonstrated in Bedient et al (2001), radar rainfall is generally preferred to gauge-interpolated rainfall.

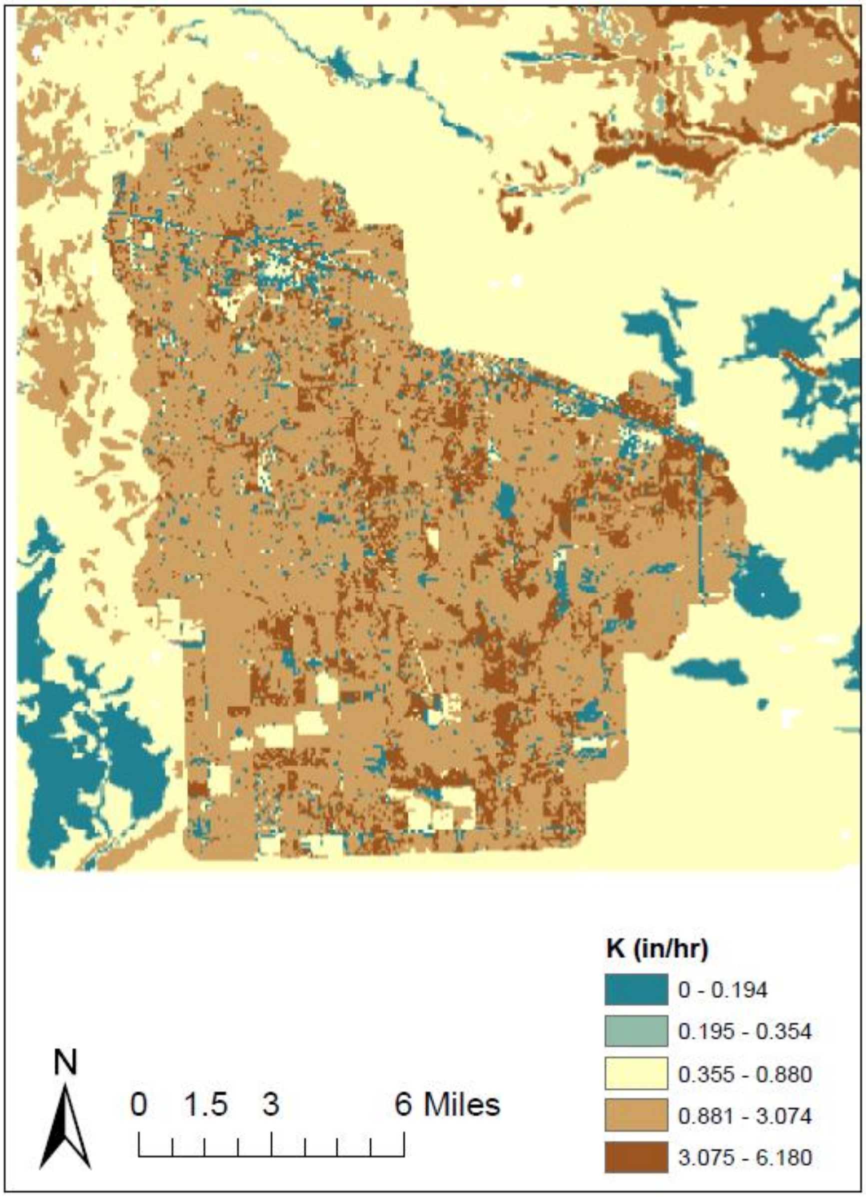



**Figure C-8. Total Hydraulic Conductivity, K, for the Upper Cypress Creek Watershed**

Initially, the model was calibrated using the soil-derived hydraulic conductivity values and infinite (unconstrained) soil depth. This method was chosen since this is the approach used to develop the official HCFCD HEC-HMS models. The calibration method consisted of modifying the channel roughness values to produce the best match in terms of peak flow and timing to the observed data. In order to produce reasonable volume estimates, the parameter of imperviousness was adjusted. This parameter was chosen because the impervious input data is from 2011, so it is likely that some additional development has occurred in the watershed since then. Upon receiving updated K values based on vegetative cover, the calibration had to be redone. Using these updated values, it was necessary to stipulate soil depth as a parameter in order to generate reasonable runoff volumes. For each storm, modeled flow hydrographs were compared to observed streamflow at four locations along the main channel of Cypress Creek and one location along Little Cypress Creek. Figure C-9 shows the location of these USGS streamflow gages.

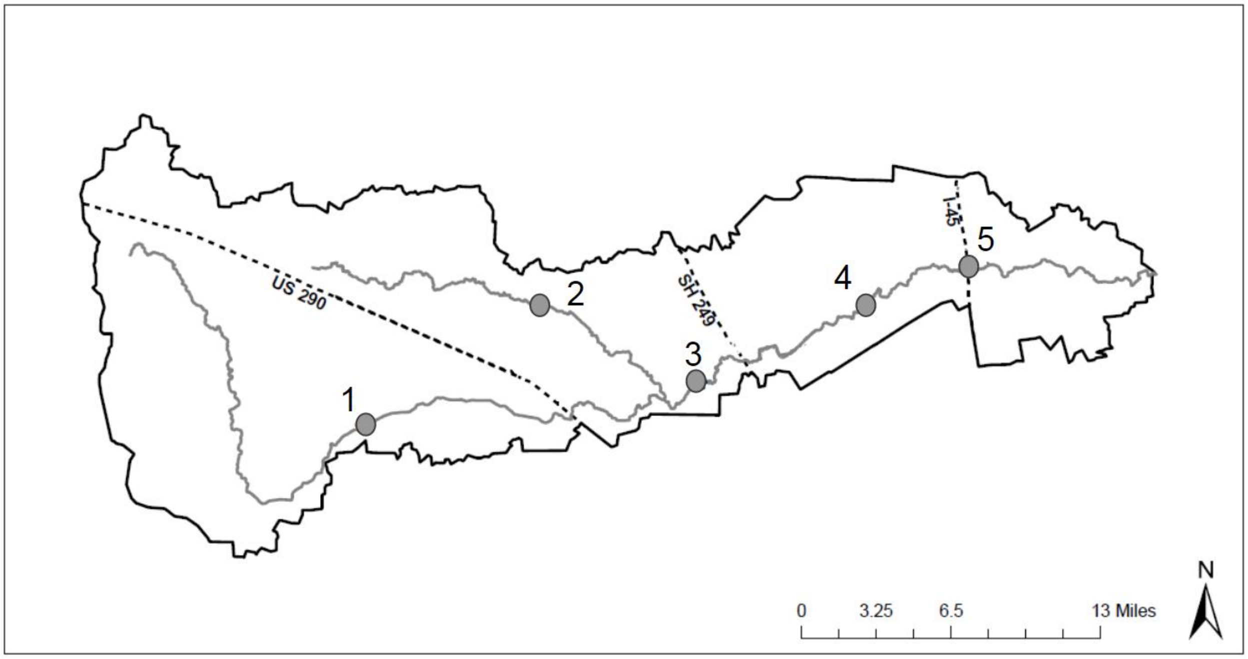



**Figure C-9. USGS Streamflow Gage Locations in the Cypress Creek Watershed**

Since Cypress Creek is a natural channel with mild slopes and slow drainage, the creek exhibits a looped rating curve at many locations across the watershed. Looped rating curves arise when the flow-discharge relationship follows one curve on the rising limb of the flood wave and a different curve on the falling limb. Since the kinematic wave approach cannot account for these rating curve effects, the falling limb of the modeled hydrograph differs significantly from the observed data. Thus, the calibration of Vflo®® focuses on matching the rising limb, timing, and peak of the hydrograph. The complex routing of the flow through Cypress Creek is achieved by utilizing the coupled 1D/2D hydraulic model HEC-RAS. Figures C-10 and C-11 show the calibration results for the April and May events.

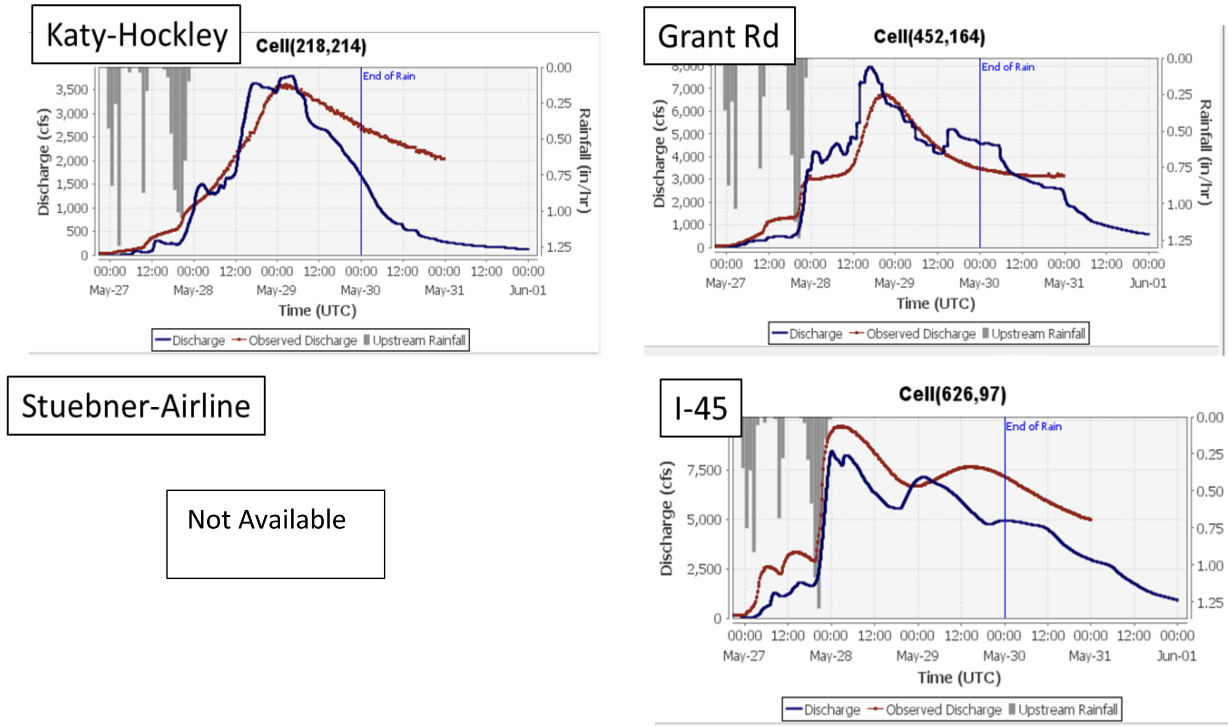



Figure C-10. Vflo® Calibration Results for May 2016 Storm Event at Selected USGS Gage Locations

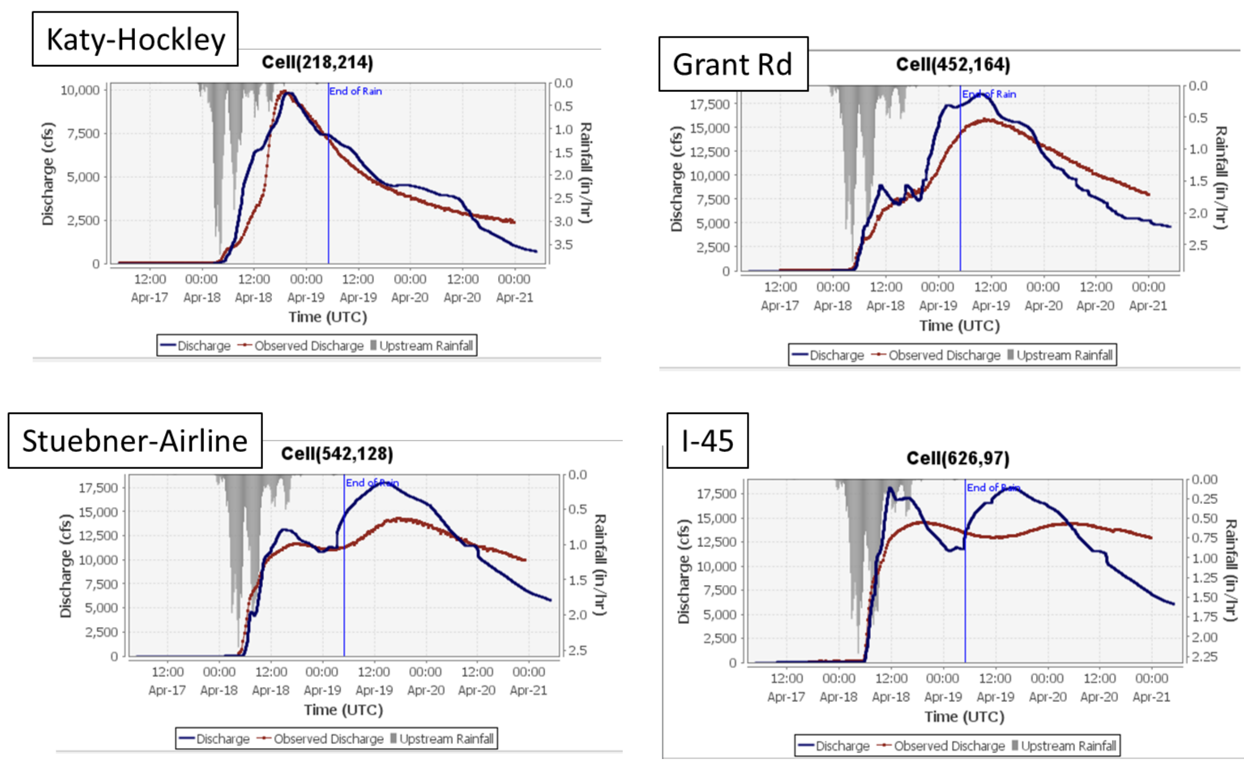



Figure C-11. Vflo® Calibration Results for April 2016 Storm Event at Selected USGS Gage Locations

## Hydrologic Modeling: Infiltration Analysis

With a calibrated Vflo® hydrologic model, a model analysis was conducted to estimate the increase in infiltration, and the corresponding decrease in runoff volume, due to changes in land cover type, by converting certain land covers (pasture and upland crops) to native prairie. This conversion was done for 4 different areas in the Upper Cypress Creek Watershed: approximate areas labeled as 20,000 acres, 30,000 acres, 50,000 acres and 101,000 acres. These areas are shown in Figure C-12.

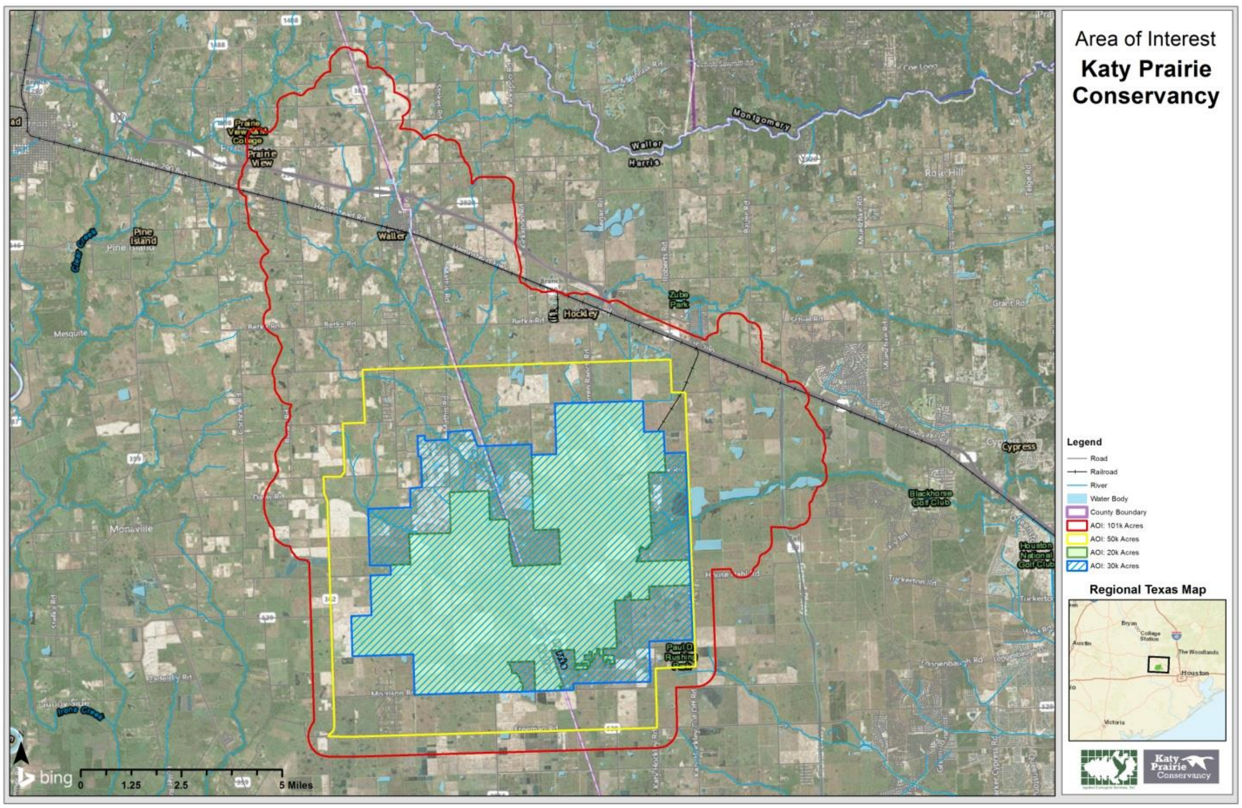



**Figure C-12. Conversion areas within the Upper Cypress Creek Watershed**

In order to evaluate the infiltration benefits of each prairie conversion scenario, and the per-acre benefit of prairie vegetation, the Vflo®® hydrologic model was run for a suite of design storms and soil depths. Infiltration volumes were produced for each and compared between scenarios. This analysis was conducted to understand how rainfall, soil depth, and hydraulic conductivity (infiltration rate, K) impact infiltration capacity and to produce runoff volume reductions under a variety of conversion scenarios.

Each land use conversion scenario was modeled in Vflo®® by importing the updated hydraulic conductivity, K, values provided by AES. Scenario 1 corresponds to baseline conditions, scenario

2 corresponds to the 20,000 acre scenario, and so on. For each land use scenario the following design storms were modeled: 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year. The following soil depth scenarios were modeled for each design storm and each land use scenario: uniform soil depths of 12 inches, 18 inches and 24 inches, as well as an unconstrained soil depth scenario and a scenario using the literature soil depth (Real Data) values.

Table C-2 shows a sample of the summary results of this suite of runs for one land cover conversion scenario. For each soil depth/design storm combination an average acre-feet of reduction in runoff volume per converted acre is computed across the four land conversion scenarios due to the corresponding increase in infiltration volume resulting from the overall increase in infiltration rate attributed to the prairie land-cover type. In general, the acre-foot reduction per converted acre is equal/similar among land use scenarios for a given soil depth and given design storm. This makes sense, since infiltration volume should increase, and runoff volume should decrease, linearly with increasing converted acres. The results of this analysis highlight regions where rainfall controls infiltration, hydraulic conductivity controls infiltration, and where soil depth controls infiltration. The full table of results is attached at the end of this appendix.

**Table C-2: Sample results of Vflo®® analysis showing Reduction in Runoff Volume in ac-ft/ac converted**

| Frequency | Rainfall | Soil Depth | | | | |
|---|---|---|---|---|---|---|
| | | 12 in | 18 in | 24 in | Unconstrained | Real Data |
| Storm | Rain (in) | ac-ft/converted acre | ac-ft/converted acre | ac-ft/converted acre | ac-ft/converted acre | ac-ft/converted acre |
| 2 | 4.1 | 0.0028 | 0.0028 | 0.0028 | 0.0028 | 0.0026 |
| 5 | 5.8 | 0.0032 | 0.0280 | 0.028 | 0.028 | 0.0110 |
| 10 | 7.1 | 0.0010 | 0.0533 | 0.053 | 0.053 | 0.0273 |
| 25 | 9 | 0.0009 | 0.010 | 0.108 | 0.108 | 0.0458 |
| 50 | 10.6 | 0.0009 | 0.005 | 0.105 | 0.15 | 0.0285 |
| 100 | 12.4 | 0.0010 | 0.002 | 0.042 | 0.20 | 0.0090 |

**Rainfall-Controlled Regions**

If soil depth is unconstrained in the infiltration analysis, this means that the soil storage capacity is assumed to be infinite. In this case, runoff volume reduction per acre of converted land increases almost linearly with increasing rainfall total. This is because as more rain volume falls over the study area, more water is available to be infiltrated and areas with higher hydraulic conductivity (i.e. natural prairie areas) will be able to store more rainwater. Thus, greater runoff reductions are achieved since the higher hydraulic conductivity values of restored land can be fully utilized to store rainwater and prevent it from becoming runoff. This phenomenon is demonstrated in Figure C-13, which shows that increasing rainfall totals (inches) result in greater per-acre runoff reductions.

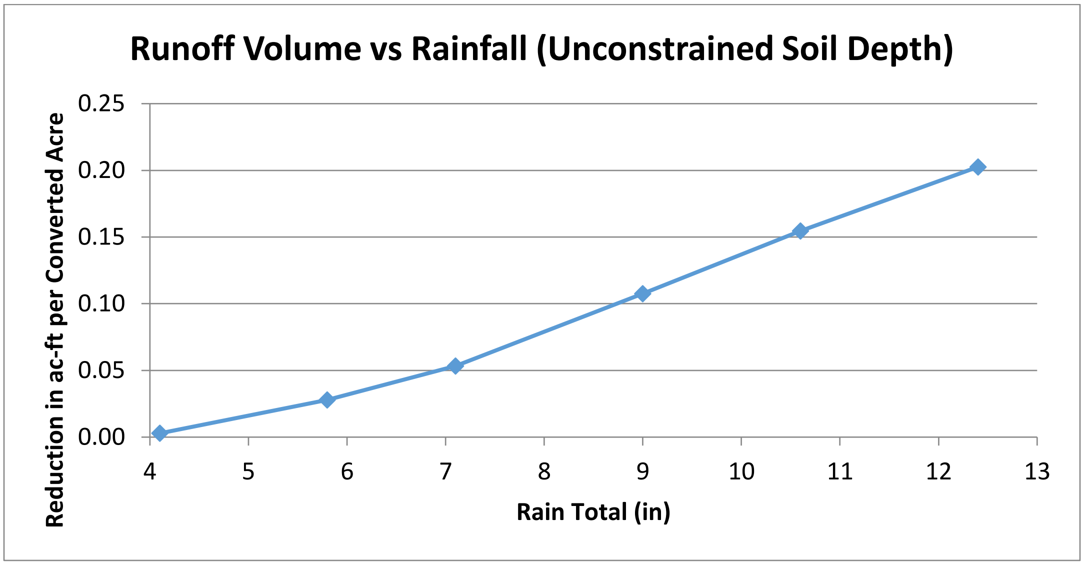



**Figure C-13: Runoff reduction volume per converted acre vs rainfall total (inches) assuming unconstrained soil depths**

**Soil Depth Controlled Regions**

If the soil depth is constrained using values of 12 inches, 18 inches, and 24 inches, it becomes clear that this parameter also controls infiltration capacity, and thus controls runoff reduction volume due to land conversion. This is because at some point during a design storm the soil storage capacity is reached, and all additional rainwater after this point is converted to runoff. If the design storm is small, and the soil storage capacity is not reached, then it is expected that runoff reduction volumes will match those of the unconstrained soil depth scenario. For example, Figure C-14 shows a graph of runoff reduction per converted acre vs rainfall total for a case with a confined soil depth of 24 inches. As shown in the graph, for rainfall totals less than 9 inches, the volume reduction increases with increasing rainfall. However, after 9 inches of rainfall, the storage capacity of the soil depth is reached and thus additional rainfall is converted directly to runoff. Correspondingly, the reduction volumes start decreasing after 9 inches of rainfall.

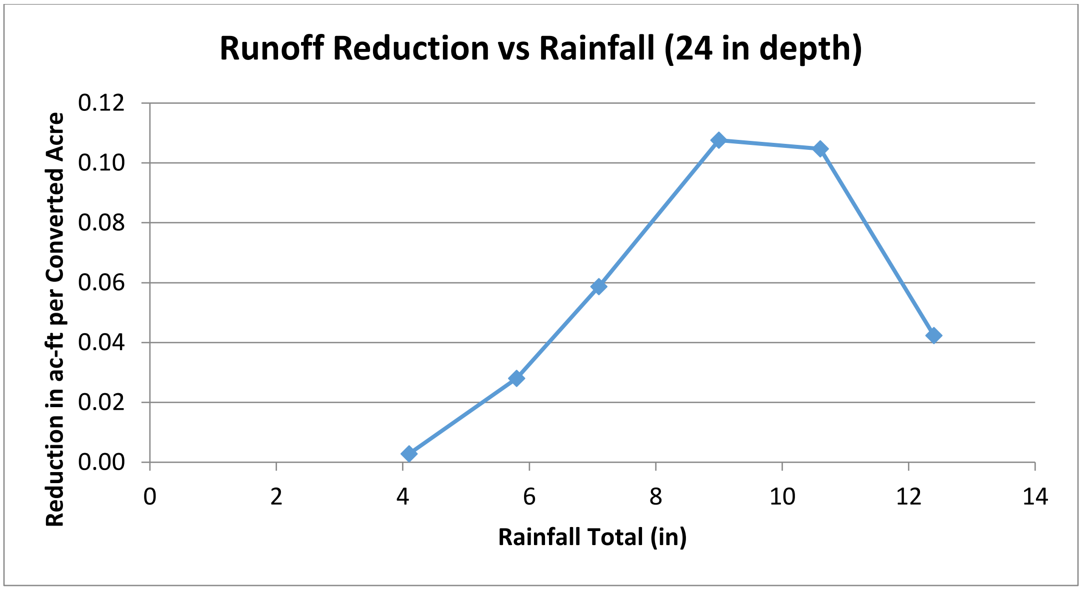



**Figure C-14: Runoff reduction volume per converted acre vs rainfall (inches) assuming 24" soil depths**

**Hydraulic Conductivity Controlled Regions**

For a given design storm magnitude, runoff reduction volumes increase with increasing soil depth. At some soil depth amount, the volume reduction per converted acre levels out and after that point increasing soil depth does not impact reduction volume. In this region, hydraulic conductivity determines the volume reductions achieved by conversion to prairie land. Figure C-15 demonstrates this phenomenon by showing reduction volume per converted acre vs soil depth for the full range of design storms. Once each curve plateaus, this is the point at which hydraulic conductivity controls infiltration capacity. For higher magnitude storms, a greater soil depth is required to reach plateau. For both a 50-year and 100-year design storm, a 24-inch soil depth does not have sufficient storage capacity to store the entire rainfall, so in these two cases the curves keep increasing until reaching their unconstrained soil depth reduction values.

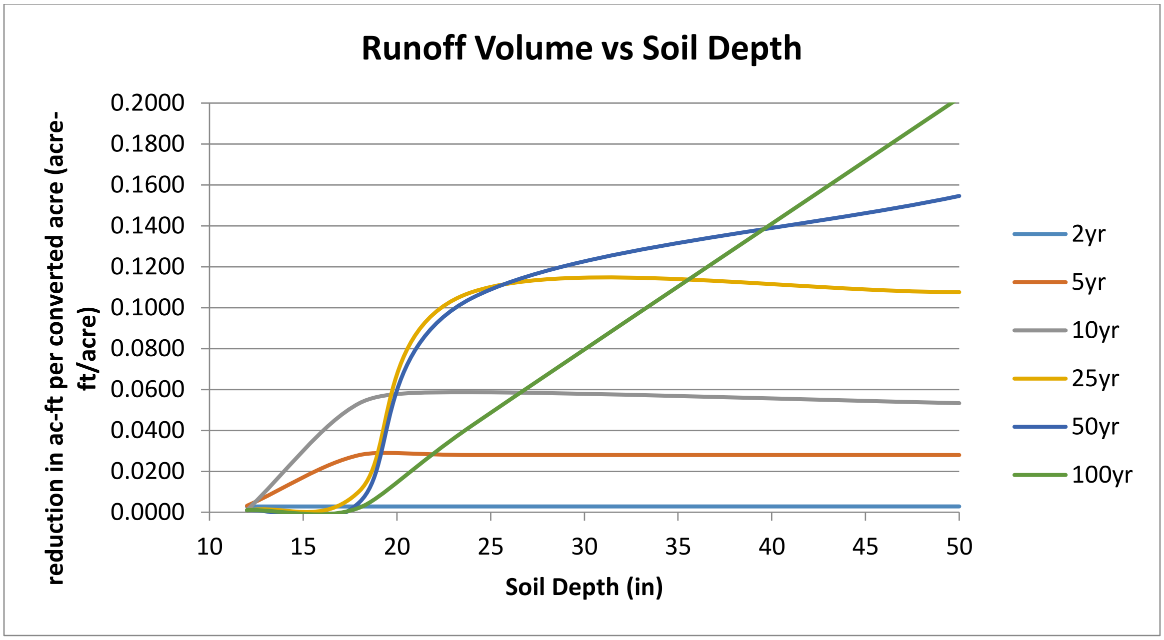



**Figure C-15: Runoff volume reduction per converted acre vs soil depth**

**Literature Soil Depth Results**

By using soil depth values based on Rawls et al (1983), it is possible to estimate the actual soil conditions of the study area. Figure C-16 shows the runoff volume reduction per converted acre vs rainfall total using the literature (“real”) soil depth values. These results indicate that the highest reductions would be around 0.046 acre-foot per acre, and would occur for a 9-inch rain (25-year storm event).

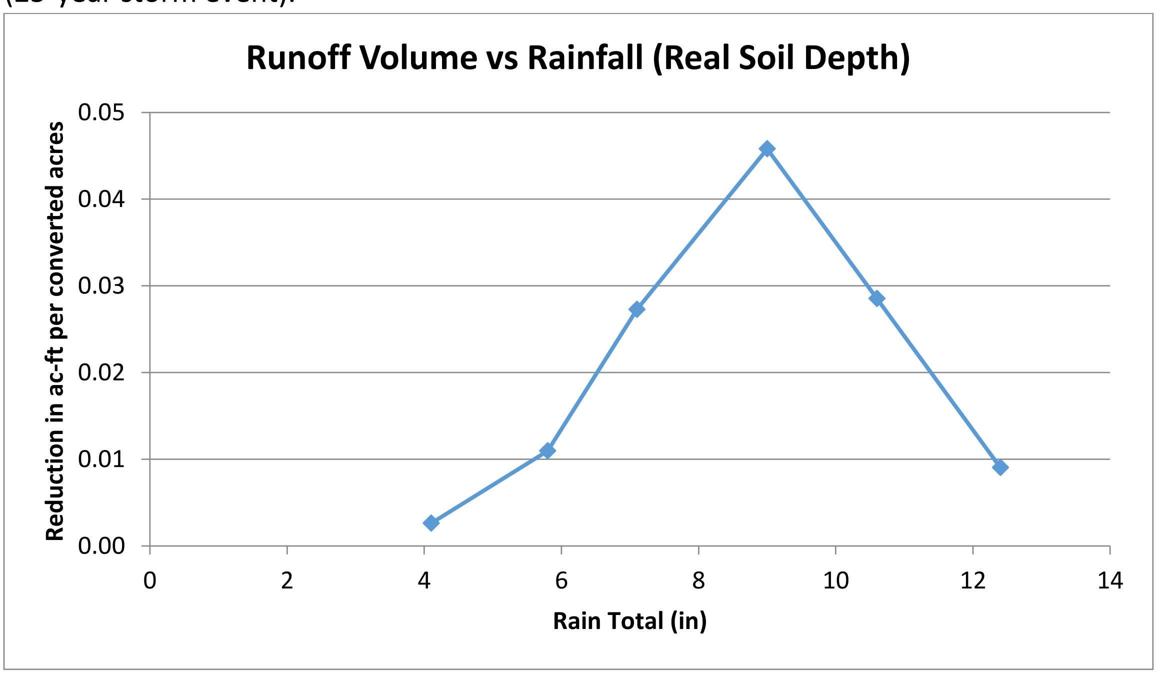



**Figure C-16: Runoff volume reduction per converted acre vs rainfall total assuming “real” soil depths**

## Appendix D – Hydraulic Modeling (HEC-RAS 1D/2D) Results

### Overview

Developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, HEC-RAS (River Analysis System) is a hydraulic model that has been used in a wide range of applications, such as floodplain assessment, flood insurance studies, and dam breach analysis. The main purpose of this program is to calculate water surface elevations at channel cross sections of interest for any given flow rate. The latest version of the software, Version 5.0.3 (USACE, 2016a), is capable of computing water surface profiles in natural or manmade channels by performing one-dimensional (1D), two-dimensional (2D), or combined 1D/2D hydraulic calculations, based on energy and momentum equations.

### Modeling Approach

For this project, hydraulic analyses of Cypress Creek and the overflow area in the upper portion of the watershed were conducted by following these steps:

1. Convert HCFCD's 1D-steady HEC-RAS model of Cypress Creek (HCFCD M3 model) into the equivalent 1D-unsteady model for the creek (see Figure D-1).
2. Develop a 2D-unsteady HEC-RAS model focusing on Upper Cypress Creek and the overflow area.
3. Connect the 1D and 2D models via lateral structures to generate a combined 1D/2D model that can simulate the hydrodynamics (i.e., flow, stage, velocity) of both the main channel and the overflow area.
4. Run various scenarios (i.e., baseline, anticipated land use conversion conditions, Plan 5) by inputting flow hydrographs generated in Vflo®® into corresponding HEC-RAS cross sections.

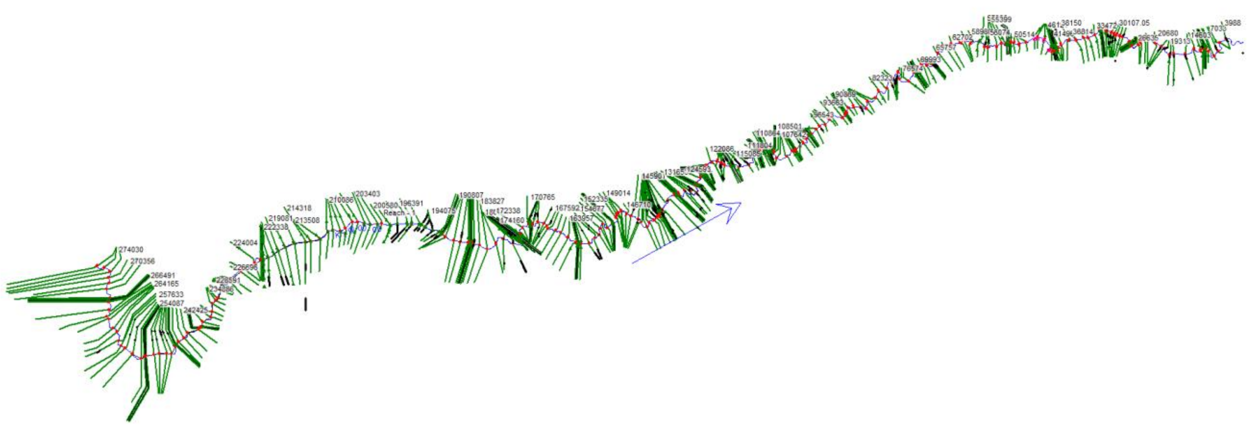


**Figure D-1: 1D-unsteady HEC-RAS geometric model of Cypress Creek**

## 1D HEC-RAS

To serve as reference, the effective hydraulic model of Cypress Creek developed by HCFCD was downloaded from the Model and Map Management (M3) system. This model is a 1D-steady model, and is used as the basis for generating the 100-year FEMA floodplain. The model generates a static water surface profile (i.e., maximum water surface elevation) along the entire channel based on peak discharges inputted at specific channel cross sections. While a 1D-steady model is useful for floodplain assessment and floodway encroachment studies, it is insufficient to model the hydraulic performances of intricate systems where volume and timing are crucial, such as the upper Cypress Creek overflow area.

In order to simulate the hydrodynamics of the upper Cypress Creek overflow area, HCFCD's 1D-steady model was converted to a 1D-unsteady model. The main advantage of an unsteady model compared to a steady model is that it can simulate the water surface profiles of entire storm hydrographs instead of just peak flows, which provides a better understanding of the system's flow and stage response over time. For this project's 1D-unsteady model, flow hydrographs were inputted as either uniform lateral inflows or as lateral inflows into specific river stations (cross sections) of the channel (e.g. see Figure D-2). These flow hydrographs were obtained from Vflo®® simulations under various storm and land use scenarios.

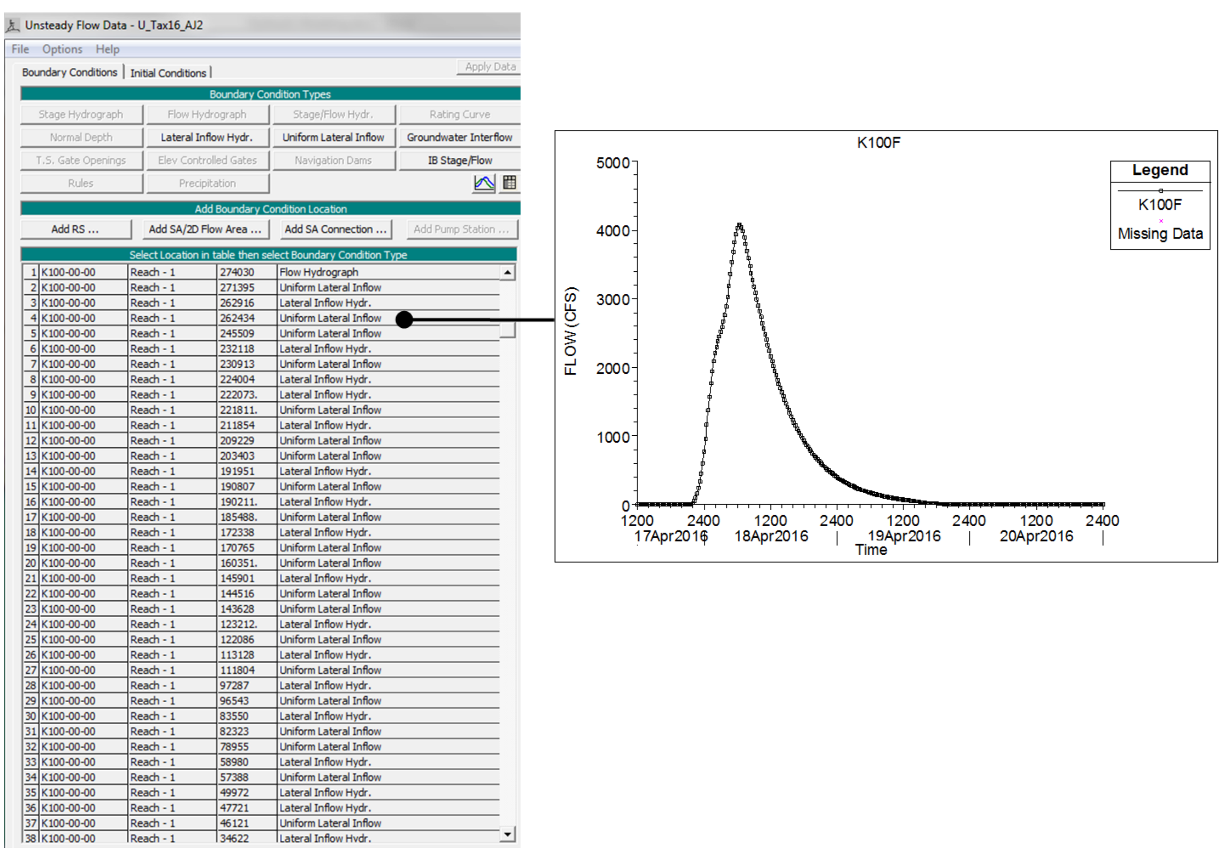



**Figure D-2: RAS unsteady flow editor and inflow hydrograph**

## 2D HEC-RAS

Starting with recent Version 5, HEC-RAS now has the ability to perform 2D hydrodynamic routing within its unsteady flow analysis component. For this project, the two-dimensional flow that occurs in the upper Cypress Creek overflow area was modeled using this 2D component of HEC-RAS, and then coupled with the 1D component of RAS (see Figure D-3). Terrain or elevation data is required to generate a 2D flow area; in this case the 2008 LIDAR data was used. The modeled 2D overflow area consists of approximately 85,000 grid cells. Although the model allows for unstructured meshes (i.e., from triangles up to eight-sided elements), most of the modeled mesh are square cells with 150-foot by 150-foot resolution. Boundary conditions for the 2D overflow area were set as normal depths at three locations. These were selected to coincide with the locations of three existing tributaries: South Mayde Creek, Bear Creek, and Langham Creek. Manning's overland roughness values were assigned to the 2D overflow area based on 2011 NLCD land cover dataset. No precipitation was inputted into the 2D overflow area, since infiltration loss could not be accounted for in HEC-RAS.

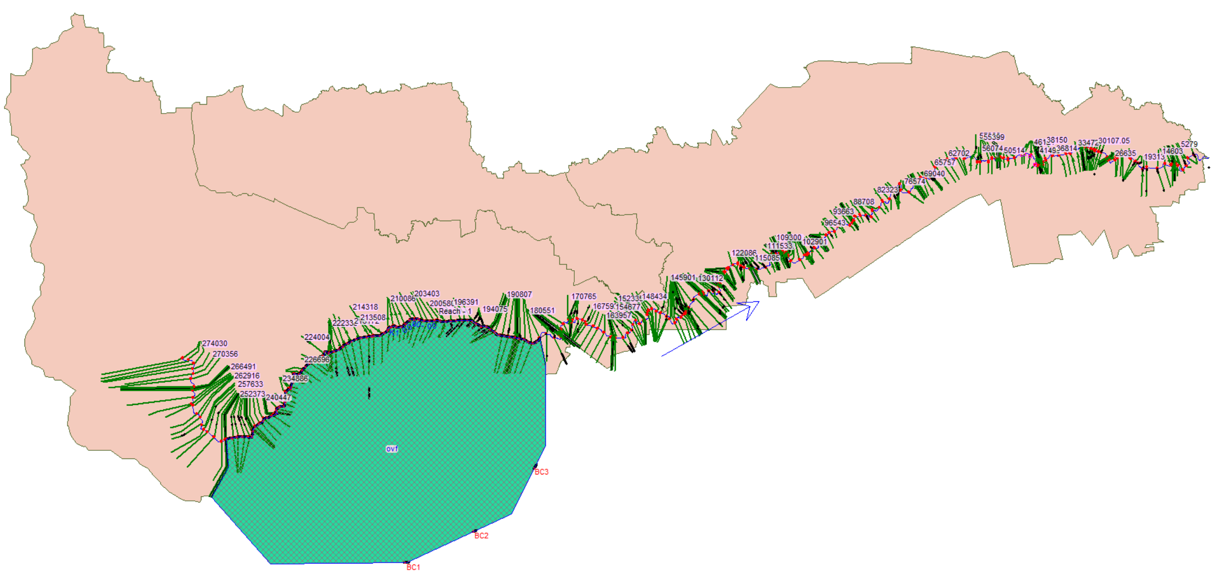



**Figure D-3: 1D/2D unsteady HEC-RAS geometric model of Cypress Creek and its overflow area**

Although 2D flow areas in HEC-RAS can be used in different ways, this project combined the 2D flow area to a 1D channel for a hybrid 1D/2D model. For this purpose, four lateral structures modeled in series were used to connect segments of the 1D channel to the 2D flow area (see Figure D-4). The four lateral structures span approximately 70,000 feet long from XS 251335 of the 1D channel to XS 180551 downstream. Each lateral structure is 20,000 feet long with the exception of the last structure, which is approximately 12,000 feet long. The lateral structures were set up next to the right bank stations of the 1D channel of the creek. When the 1D water surface elevation reaches and exceeds the lateral structure height, water will spill over and propagate throughout the 2D flow area. Thus, the 2D flow area includes the right overbank areas of Cypress Creek and the overflow area within the Addicks Watershed.

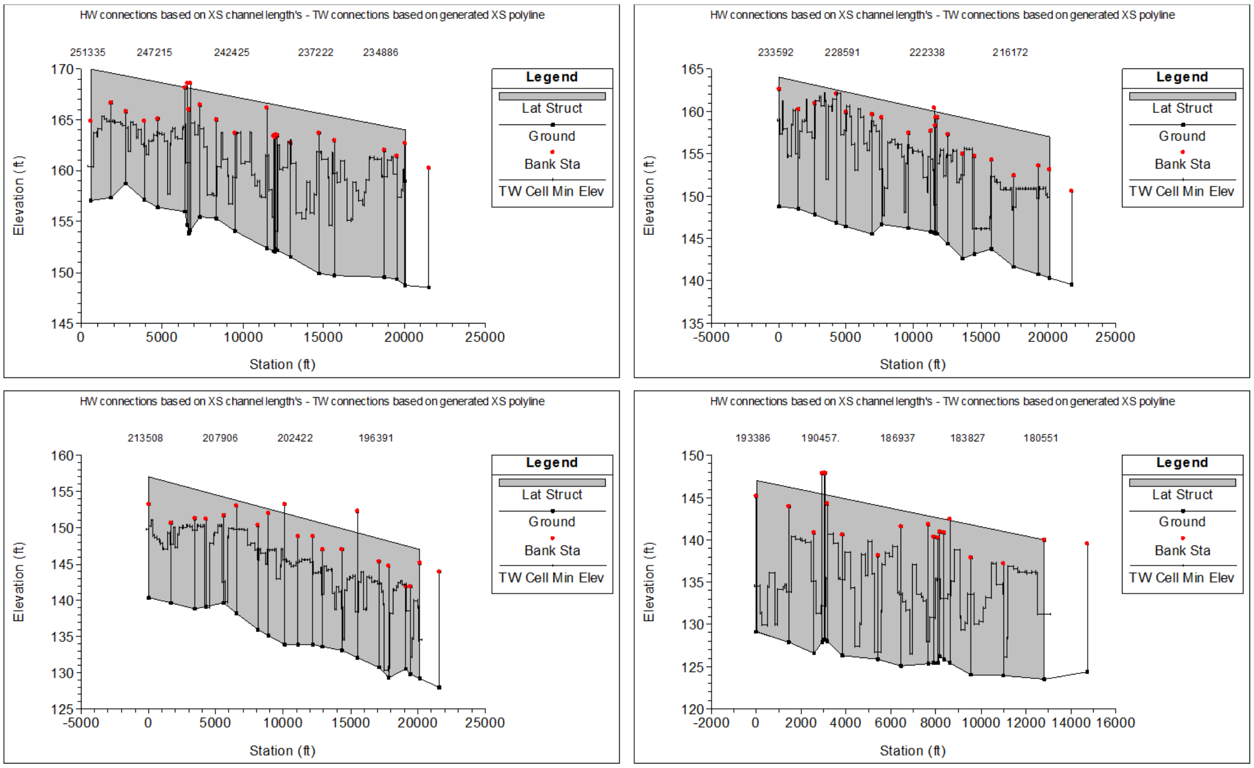



**Figure D-4: Modeled lateral structures for 1D/2D connection**

## Management Plan 5 Setup

In this project, an evaluation was made of HCFCD's Management Plan 5, a proposed levee/berm system with outlets at Cypress Creek and Bear Creek to detain Cypress Creek flows, including overflows, during major storm events. This Plan 5 was represented in the HEC-RAS 1D/2D model by a levee structure with culverts. Since design specifications of Plan 5 were unavailable, a uniform levee crown elevation of 176 feet was selected to prevent overtopping. The levee spans from the 1D channel portion (XS 222200) near Katy-Hockley to the west end portion of the 2D overflow area at Longenbaugh (see Figure D-5). The levee was modeled as inline structures at both the 1D and 2D portions of the model. Plan 5's Cypress Creek outlet structure was modeled as a single concrete box culvert (12 ft. high and 10 ft. wide); a similar box culvert (10 ft by 10 ft) was modeled near Bear Creek to represent the Bear Creek outlet structure (see Figure D-6).

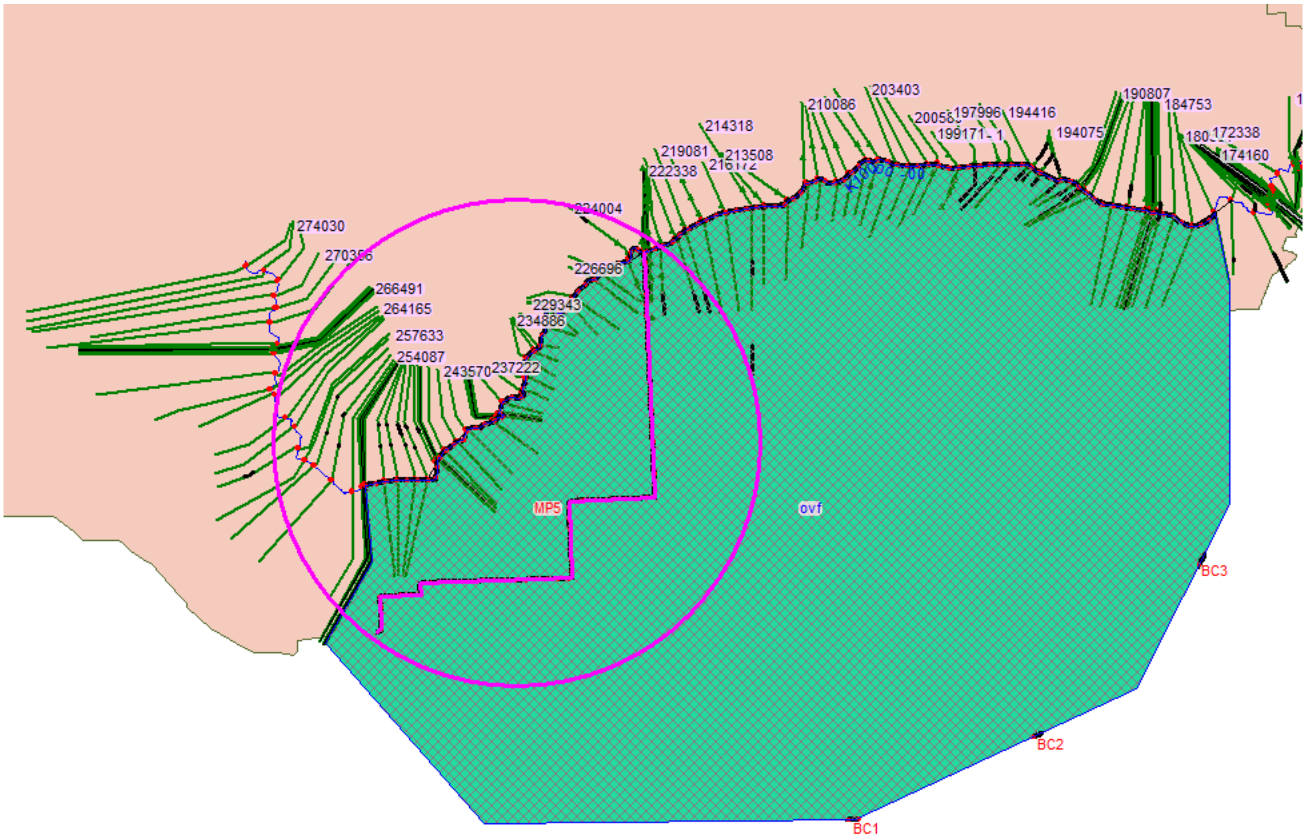
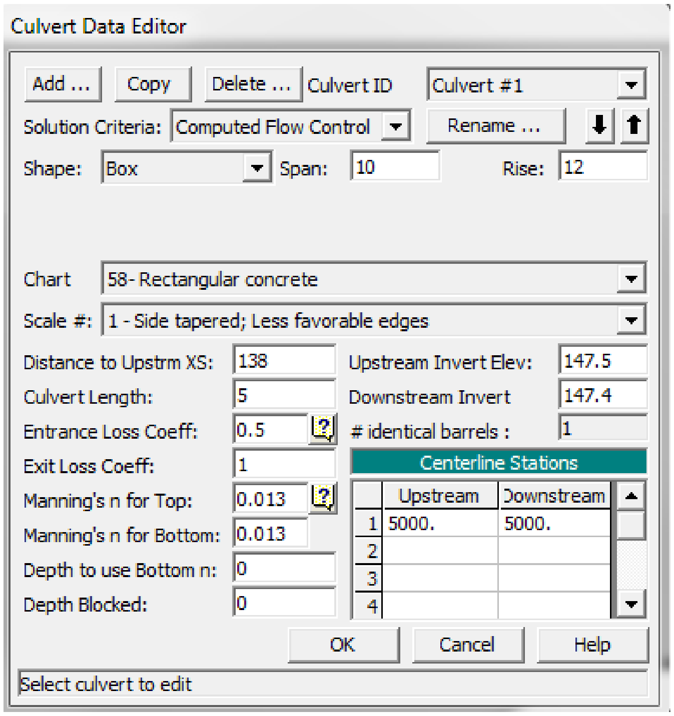



**Figure D-5: 1D/2D unsteady HEC-RAS geometric model of Cypress Creek and overflow area for Plan 5**



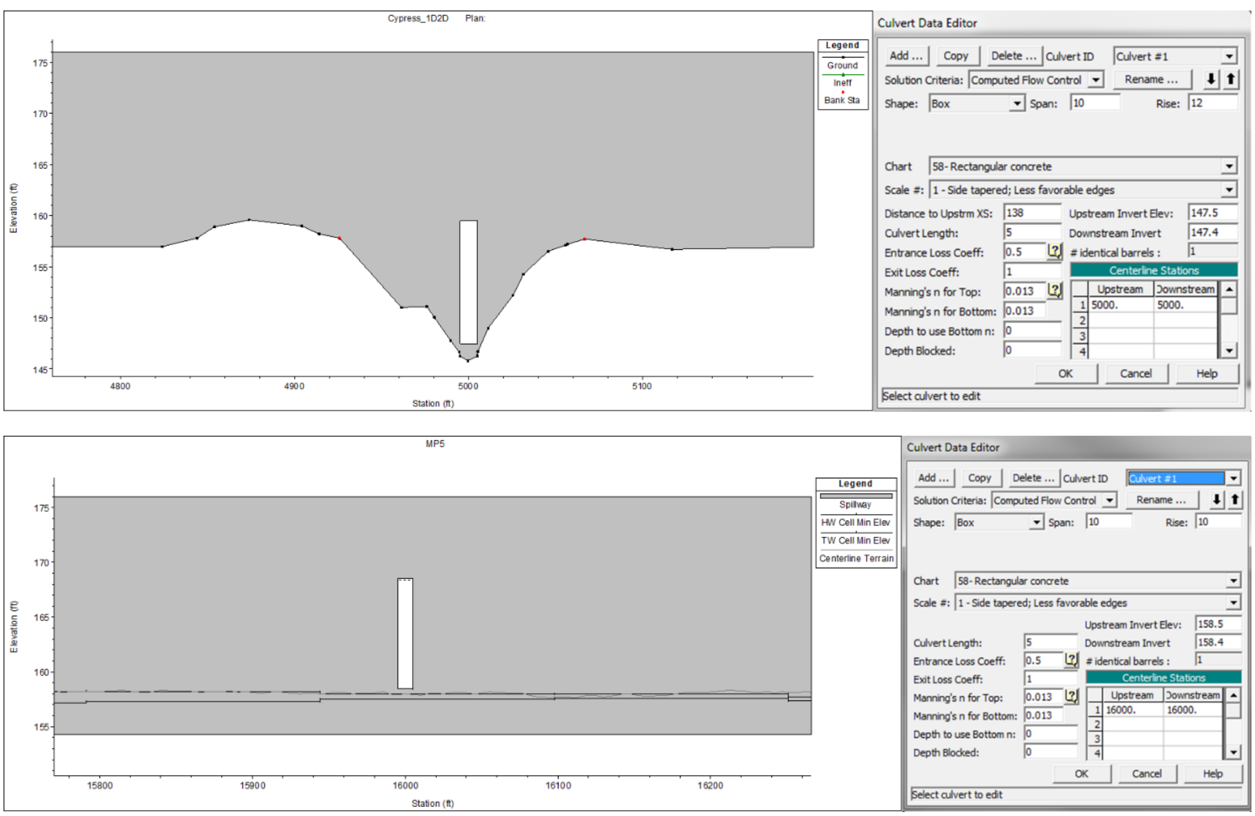




**Figure D-6: Cypress Creek (top) and Bear Creek (bottom) inline structure and culvert**

## Model Validation

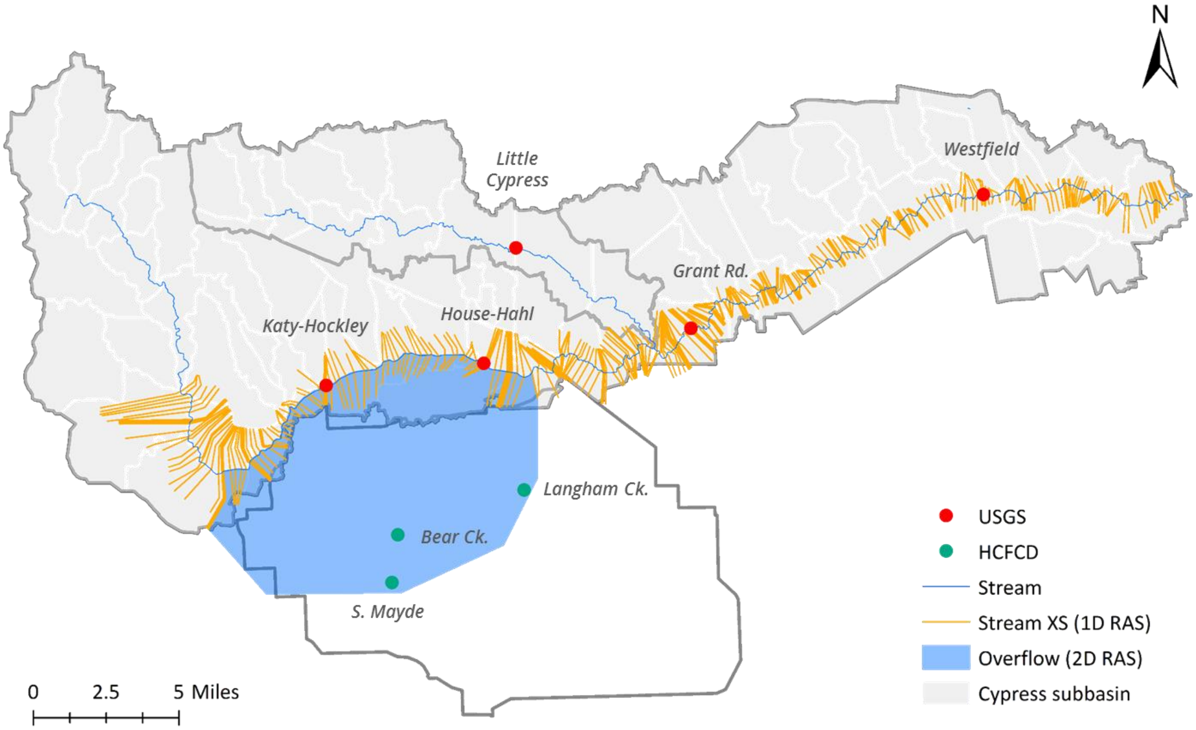
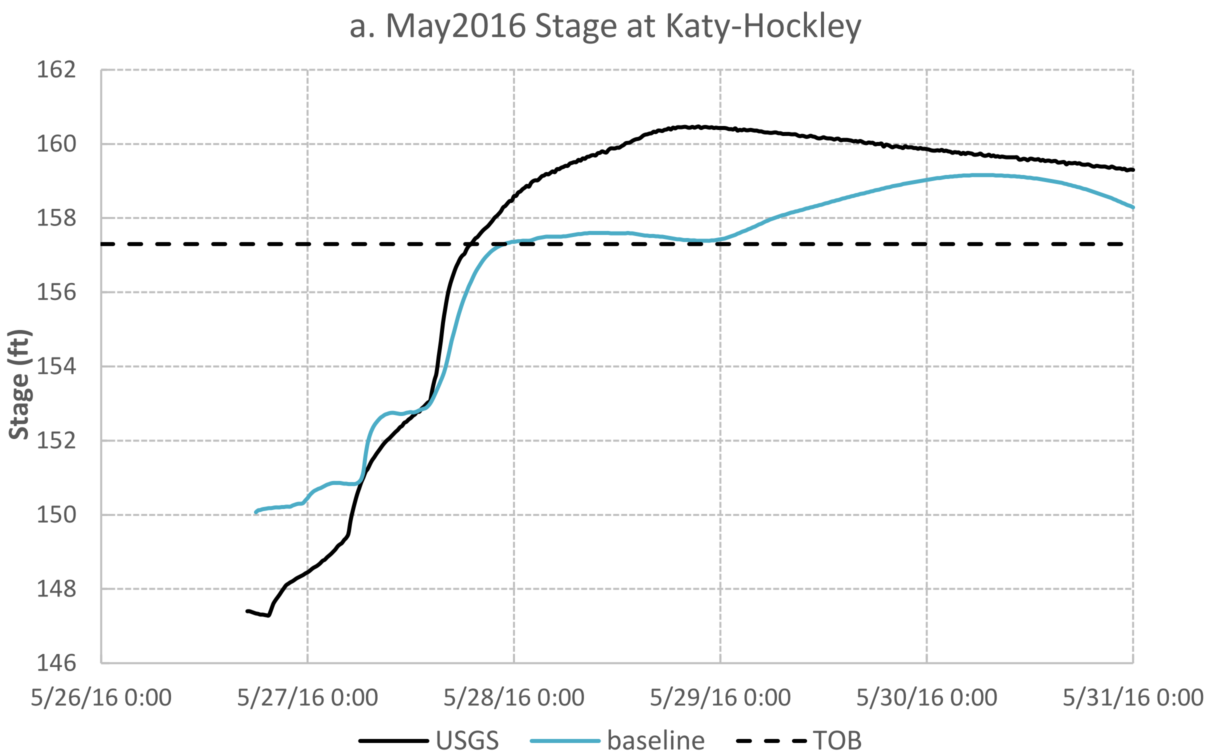
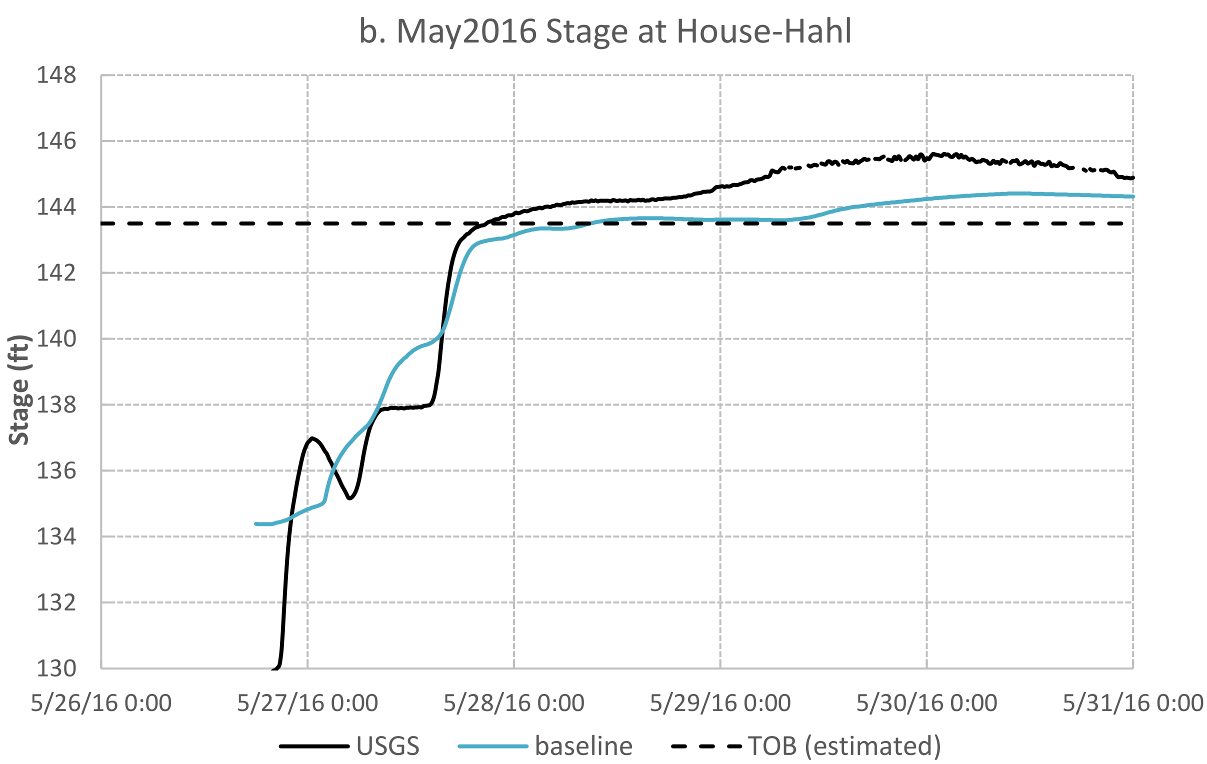


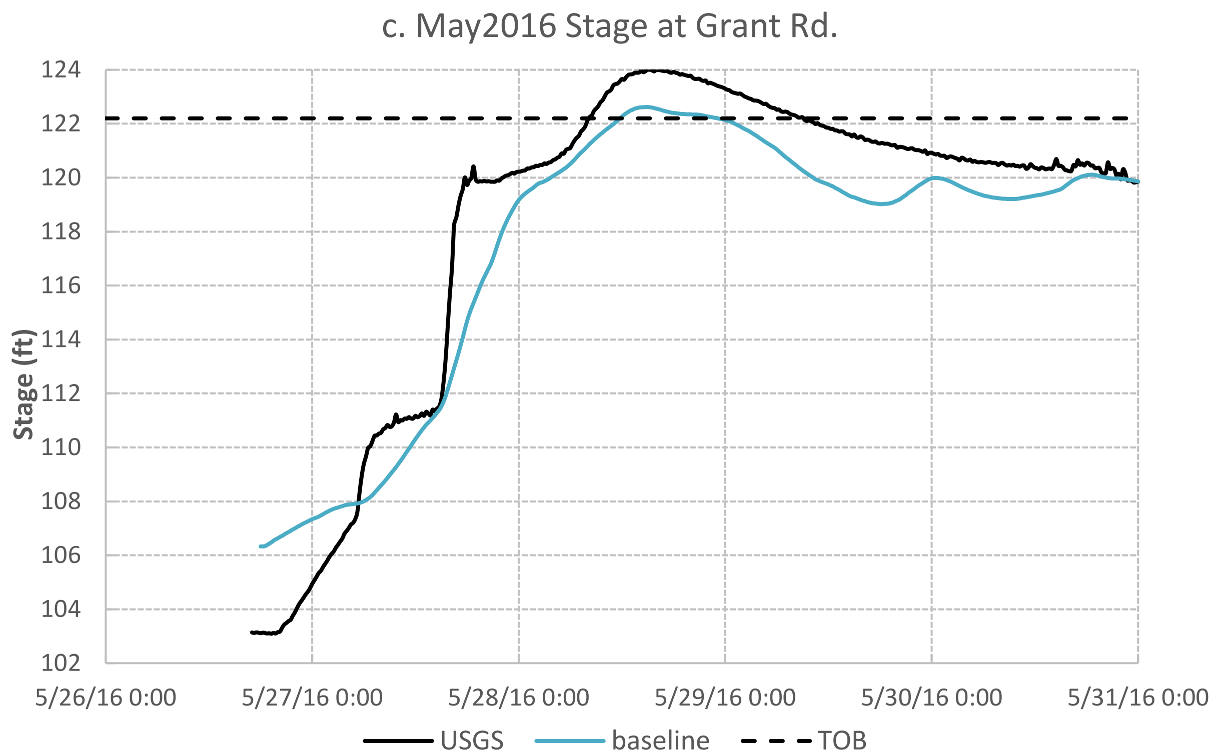

**Figure D-7: 1D/2D HEC-RAS Model Domain Schematic and Gage Locations**

Figure D-7 shows a schematic of the 1D/2D HEC-RAS model domain and several stream gages within the Cypress Creek watershed and the overflow area. To validate the Baseline 1D/2D HEC-RAS model, the May 2016 storm and the Tax Day (April) 2016 storm were simulated. Modeled water surface elevations (stages) along Cypress Creek were compared to observed stages at four corresponding USGS gage locations: Katy-Hockley, House-Hahl, Grant Rd., and Westfield.

The following figures (D-8a-d and D-9a-d) show stage comparisons between modeled and observed data for the May 2016 and Tax Day 2016 storms, respectively. In the early periods of both storms, the model started with higher water surface elevations compared to observed data. This was due to the model needing initial flow at certain upstream cross sections to ensure model stability. Later with both storms, as the rainfall occurred and the flows and water levels rose in the creek and the flood progressed downstream, the modeled results show slightly lower stages compared to the observed data. Despite these discrepancies, their overall timing and response match very well with the observed data.  Exact matches were not expected as the data used in the model to represent the hydraulic response of the creek does not represent 2016 geometric conditions along the creek, especially in the area of the Bridgelands' development.


a. May2016 Stage at Katy-Hockley
Stage (ft)
162
160
158
156
154
152
150
148
146
5/26/16 0:00
5/27/16 0:00
5/28/16 0:00
5/29/16 0:00
5/30/16 0:00
5/31/16 0:00
USGS
baseline
TOB


b. May2016 Stage at House-Hahl
Stage (ft)
148
146
144
142
140
138
136
134
132
130
5/26/16 0:00
5/27/16 0:00
5/28/16 0:00
5/29/16 0:00
5/30/16 0:00
5/31/16 0:00
USGS
baseline
TOB (estimated)



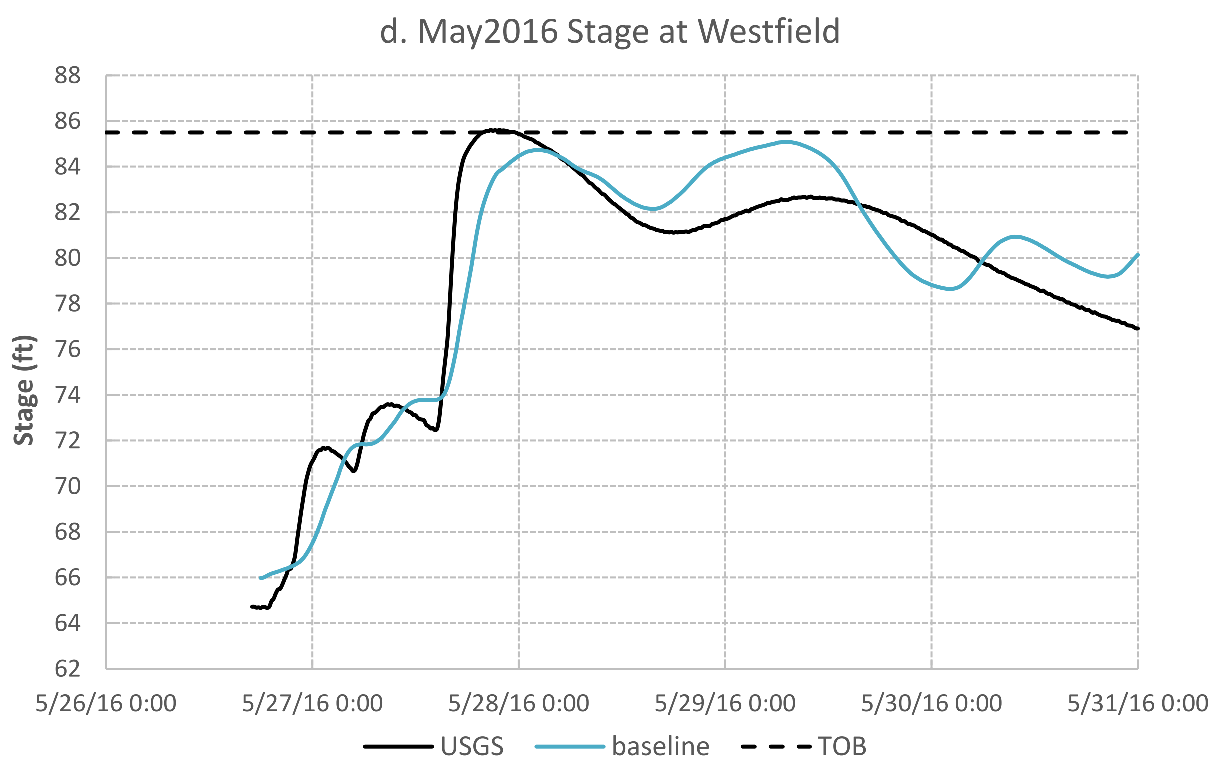
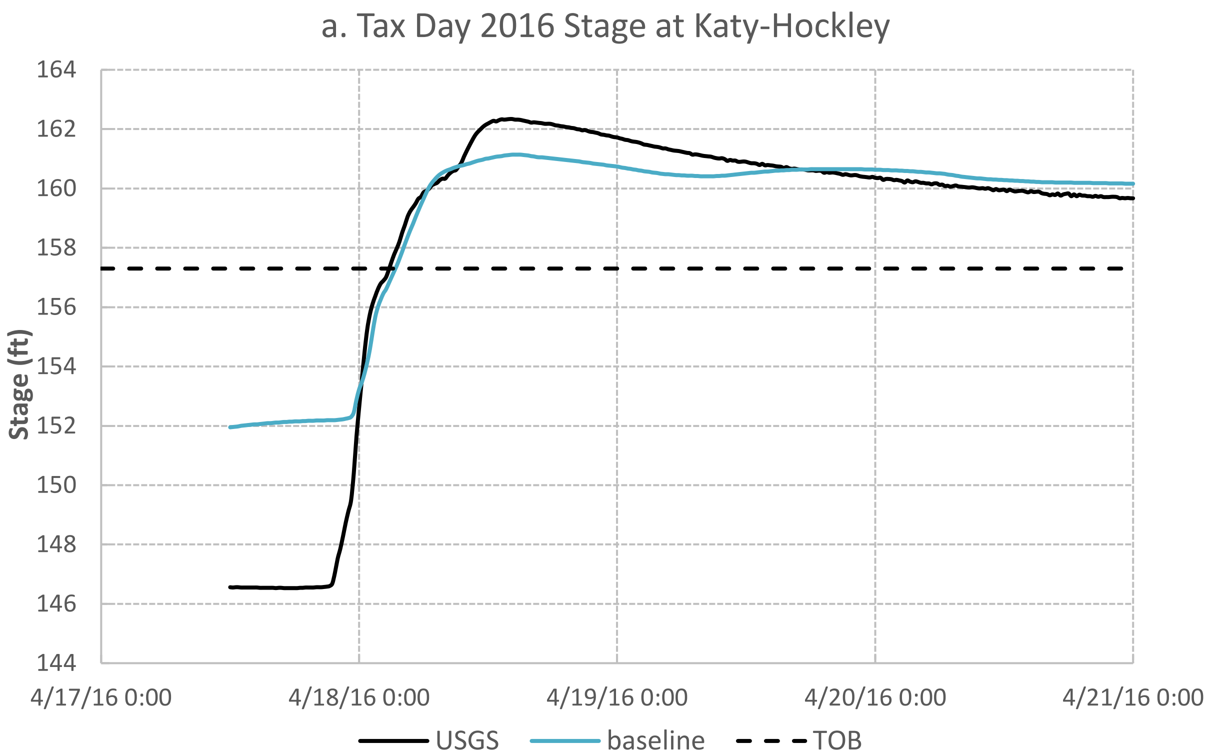
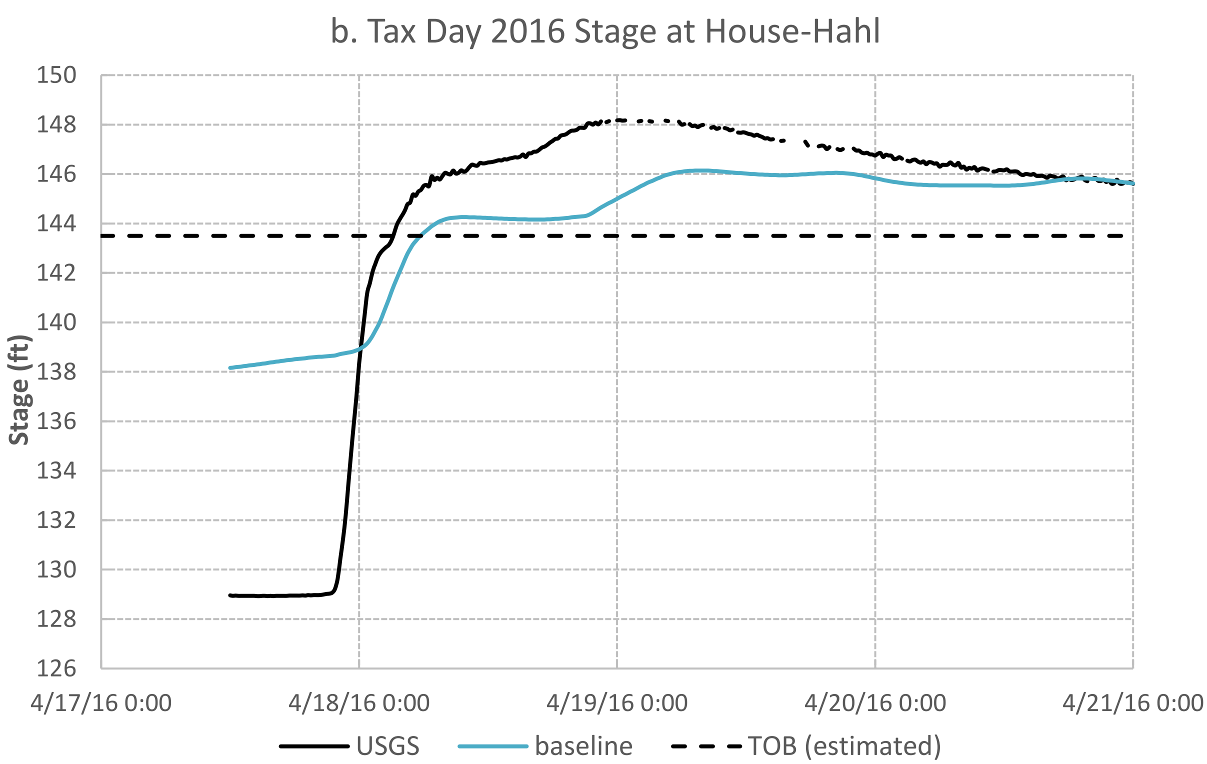
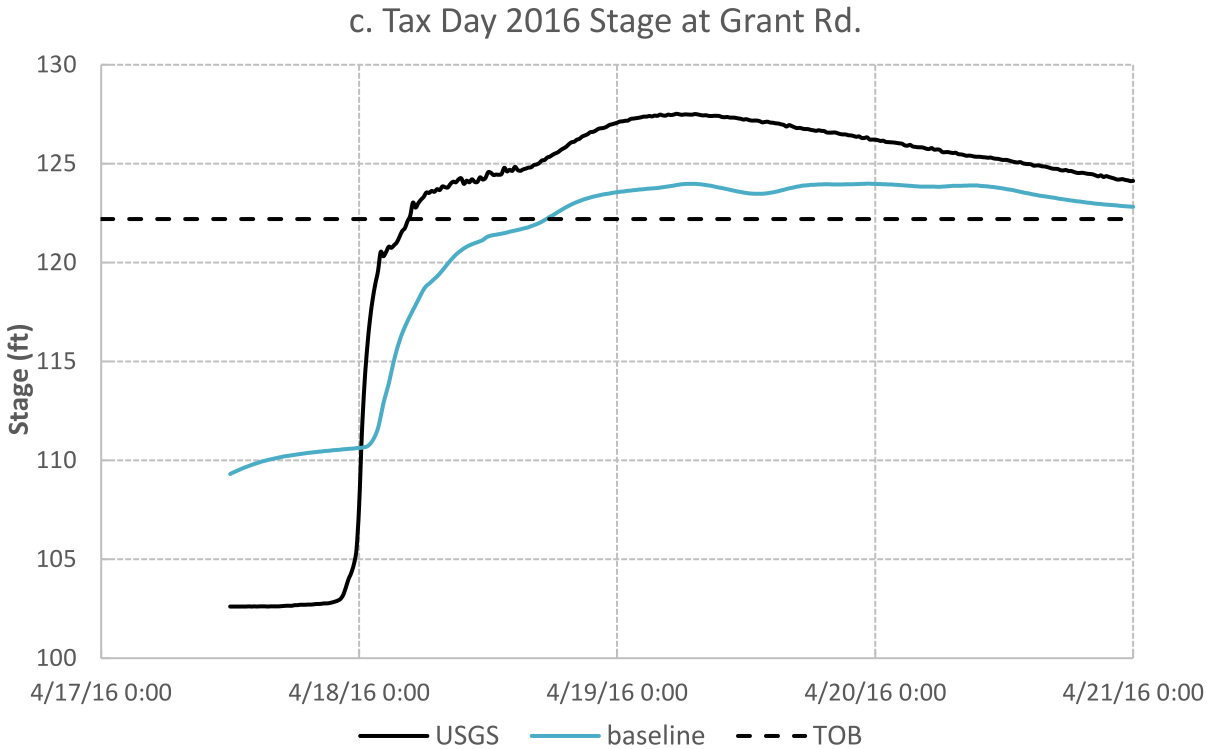




**Figure D-8a-d: Modeled stage (baseline) vs observed for the May 2016 Storm**


a. Tax Day 2016 Stage at Katy-Hockley
Stage (ft)
164
162
160
158
156
154
152
150
148
146
144
4/17/16 0:00
4/18/16 0:00
4/19/16 0:00
4/20/16 0:00
4/21/16 0:00
USGS
baseline
TOB


b. Tax Day 2016 Stage at House-Hahl
Stage (ft)
150
148
146
144
142
140
138
136
134
132
130
128
126
4/17/16 0:00
4/18/16 0:00
4/19/16 0:00
4/20/16 0:00
4/21/16 0:00
USGS
baseline
TOB (estimated)



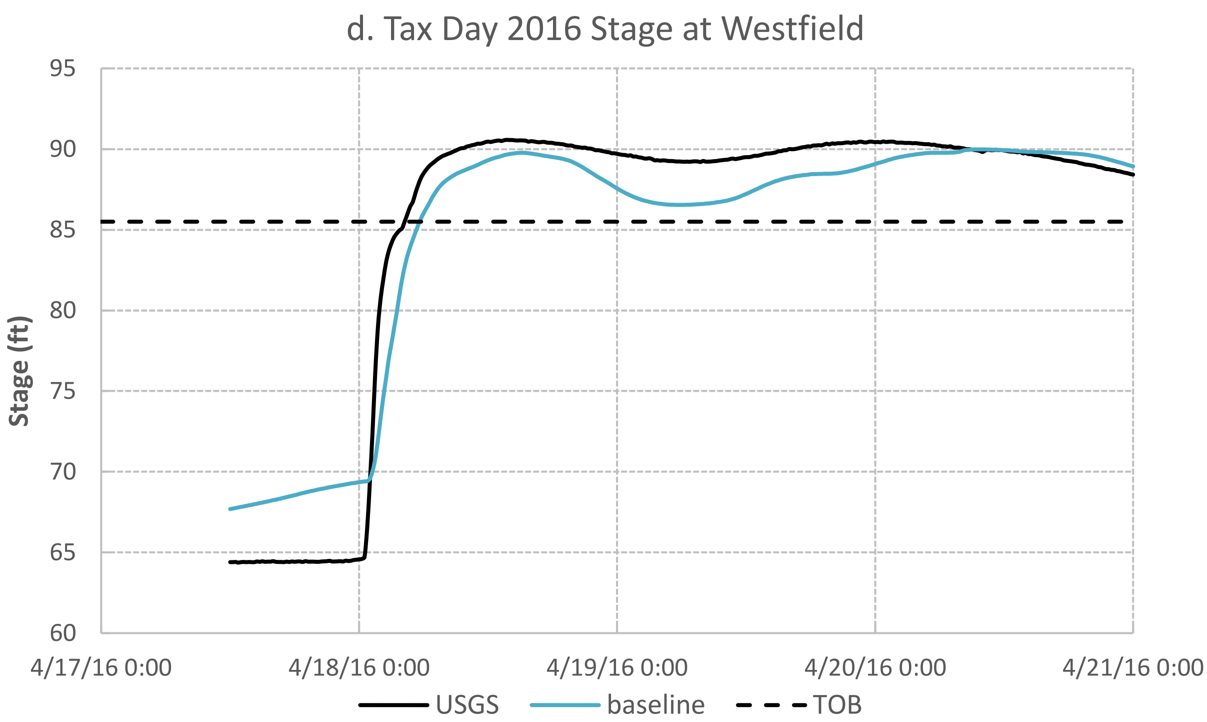
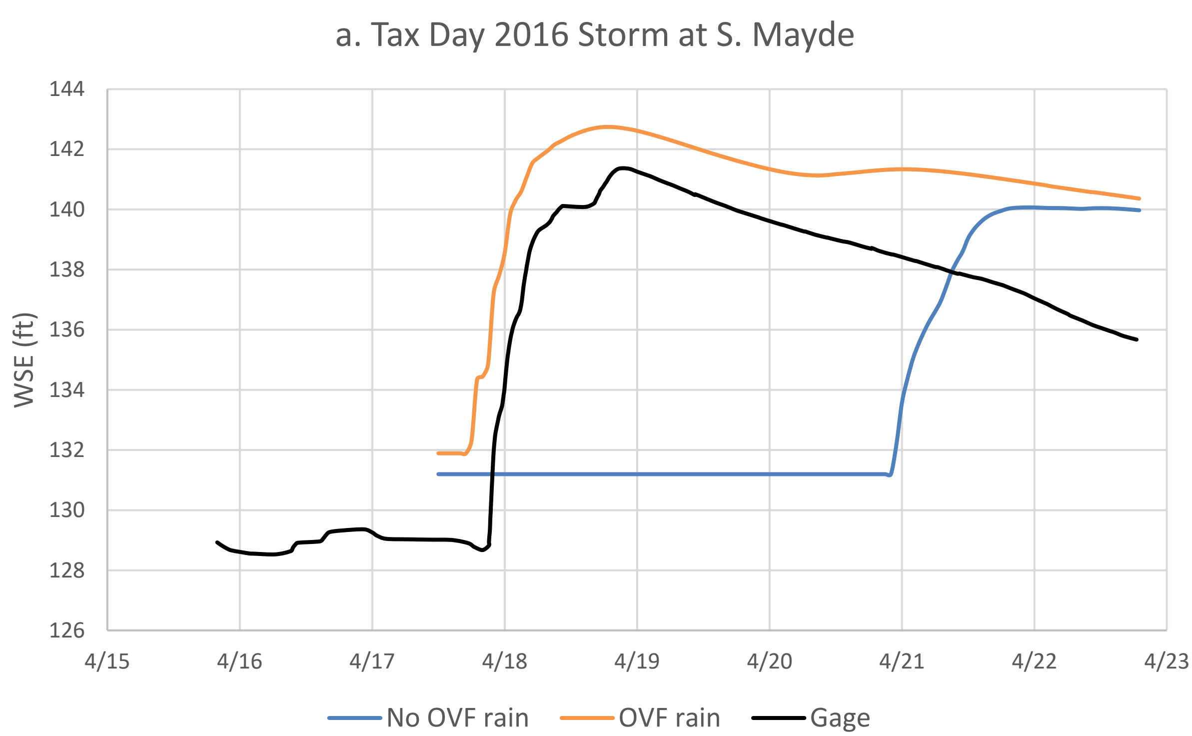
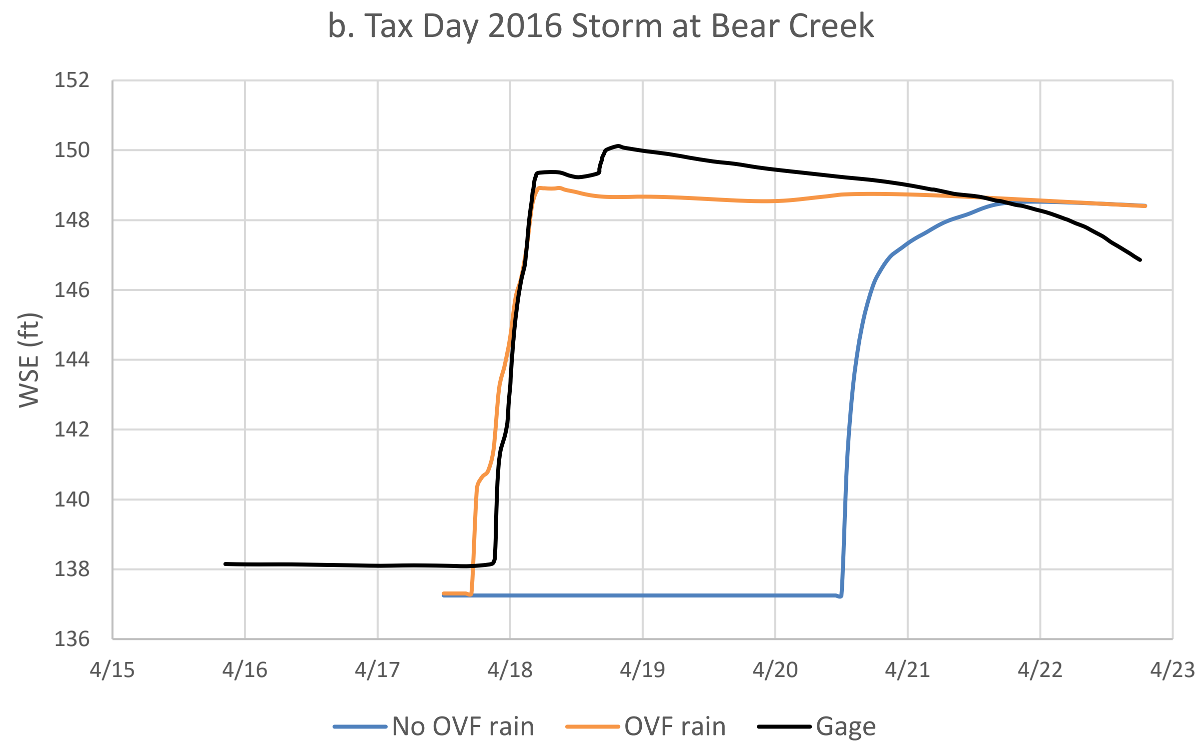




**Figure D-9a-d: Modeled stage (baseline) vs observed for the Tax Day (April) 2016 Storm at Cypress Creek**

In addition to the USGS gages along Cypress Creek, there are three HCFCD gages within the modeled 2D overflow area in the Addicks Watershed (i.e., on S. Mayde, Bear, and Langham creeks). Unlike the USGS gages, however, these HCFCD gages were only used for limited comparison purposes due to two reasons. First, HEC-RAS 2D, in its current version, does not allow for spatially-variable rainfall. This means that a single rainfall hyetograph would have to be applied to the entire 2D domain. Next, HEC-RAS 2D is also currently incapable of accounting for infiltration loss. Consequently, all pervious surfaces are essentially treated as impervious cover in the 2D domain. These limitations are not a huge issue in hypothetical scenario-type analyses (e.g., worst-case scenario for flood mitigation design), but they pose a challenge in event-type analyses (i.e., hindcasting of historical storms).

The following figures (D-10a-c) show modeled water surface elevations compared to the observed stages at the three HCFCD gage locations for the Tax Day 2016 storm. The "No OVF rain" results assumed no precipitation in the 2D overflow area, and correspondingly its stage was a direct result of the Cypress Creek overflow. In contrast, the "OVF rain" results were obtained by applying a uniform rainfall (i.e., observed rainfall from the Bear Creek HCFCD gage) to the entire 2D overflow area without any infiltration loss. Therefore, the modeled stage represented both the Cypress overflow and the local basin inflows.





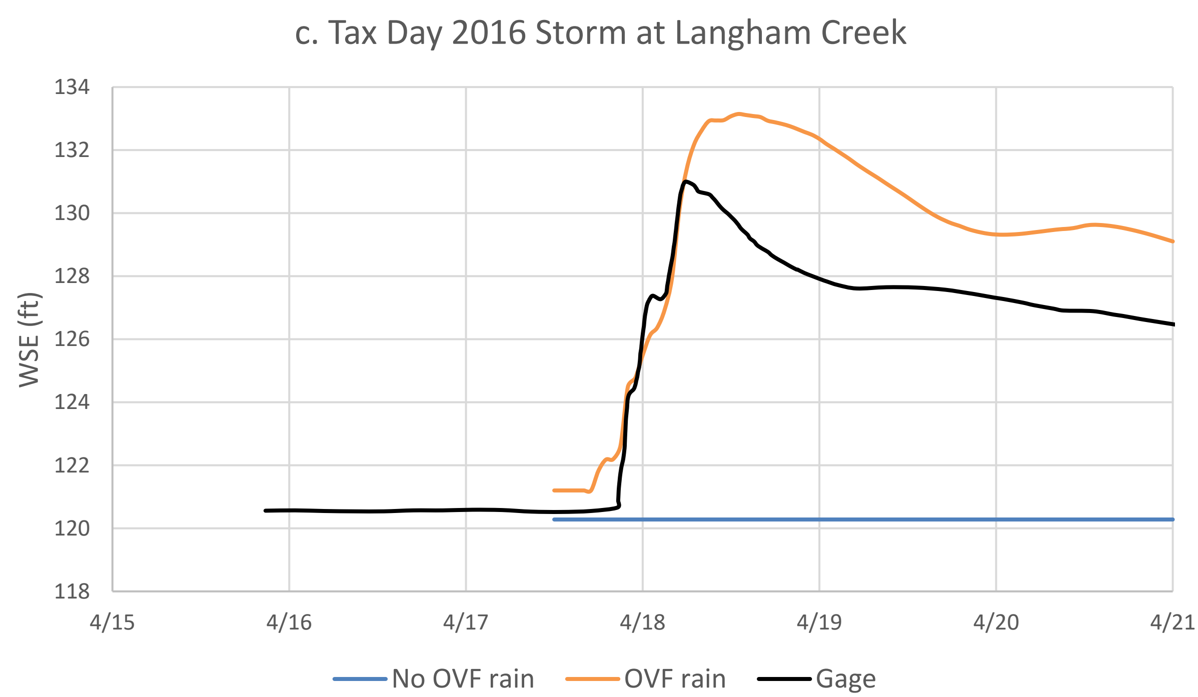
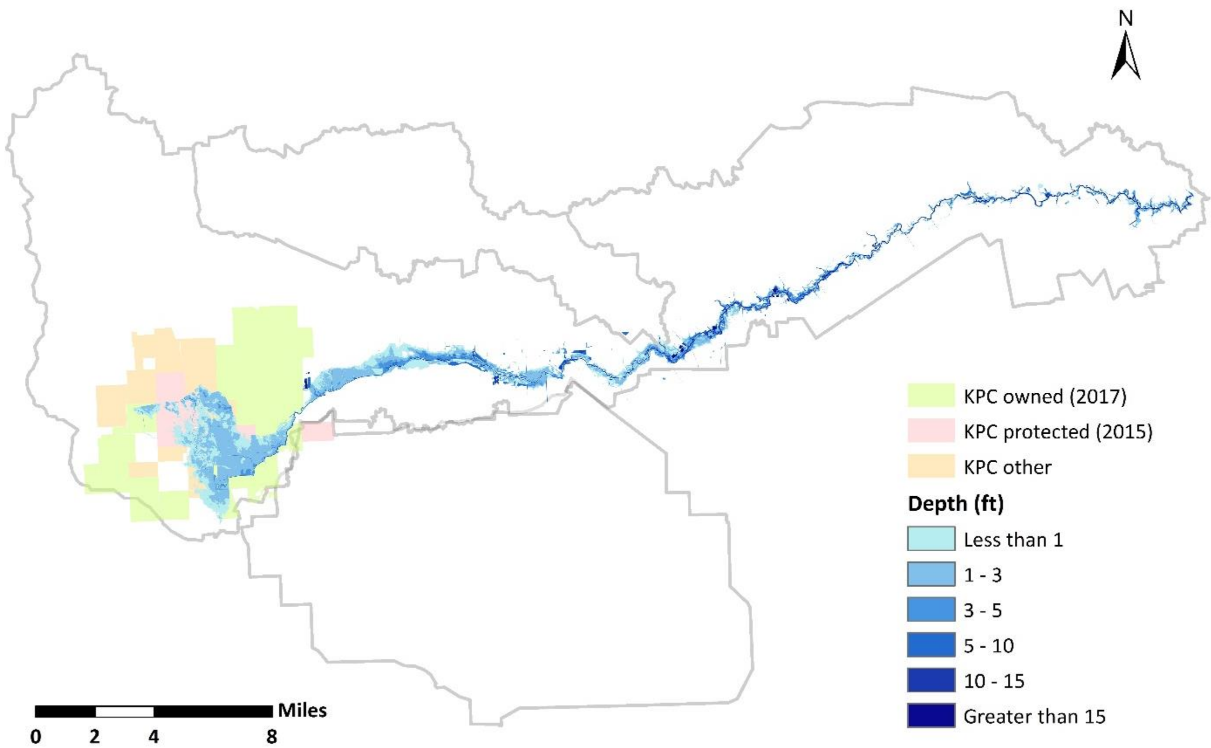




***Figure D-10a-c: Modeled stage (baseline) vs observed for the Tax Day (April) 2016 Storm at overflow tributaries***

These results indicated that the water surface elevations at the three gages were primarily caused by local basin inflows. Since the overflows from Cypress Creek were shown to reach the gage locations much later, they were unlikely to have contributed to the observed peak stages. Comparing the “OVF rain” results across the three gage locations, the results at Bear Creek showed the best match with observed data. This is because the “OVF rain” scenario was run by applying observed rainfall at the Bear Creek gage for the entire 2D overflow area. As such, it was unsurprising to see that the “OVF rain” results at S. Mayde and Langham creeks did not match observed data as well as the one on Bear Creek.

Based on this 1D/2D HEC-RAS model for Cypress Creek and its overflow area, the maximum inundation modeled for both the May 2016 and Tax Day 2016 is shown in Figure D-11.



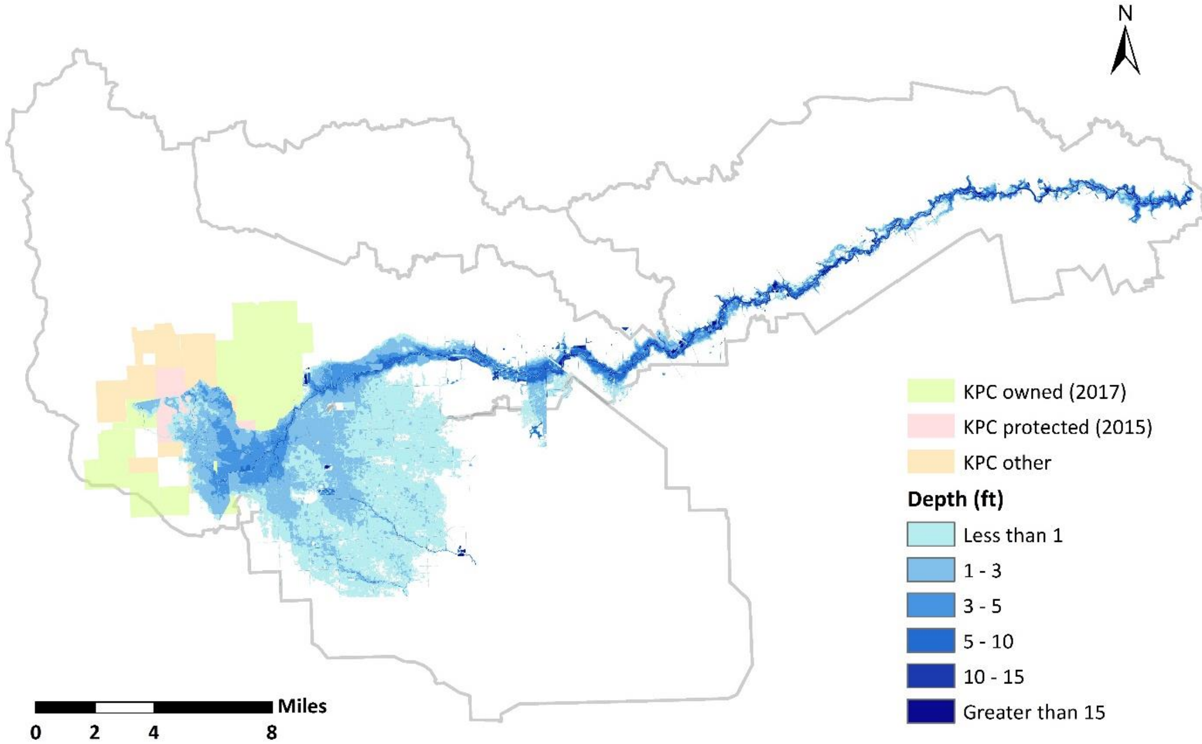



**Figure D-11: Max inundation for the May 2016 Storm (top) and the Tax Day (April) 2016 Storm (bottom)**

## Scenario Comparison

After validating the HEC-RAS 1D/2D model under current development conditions (Baseline Scenario 1), the model is then used to quantify the flood reduction benefits of converting certain land cover types to prairie, based on the amount of overflow crossing the Cypress-Addicks watershed divide. For this purpose, HEC-RAS was run without applying any precipitation in the 2D overflow area, since the purpose of these simulations was to compute the amount of overflow occurring from Cypress Creek into the Addicks Watershed. Various prairie conversion scenarios (i.e., Scenarios 2, 3, 4, and 5) under 2 design storms (10-yr and 100-yr) are simulated, and their resulting overflows and water levels are compared to the Baseline scenario. Figure D-12 shows the location of the watershed divide that marks the interbasin transfer from Cypress Creek to Addicks Reservoir watershed.

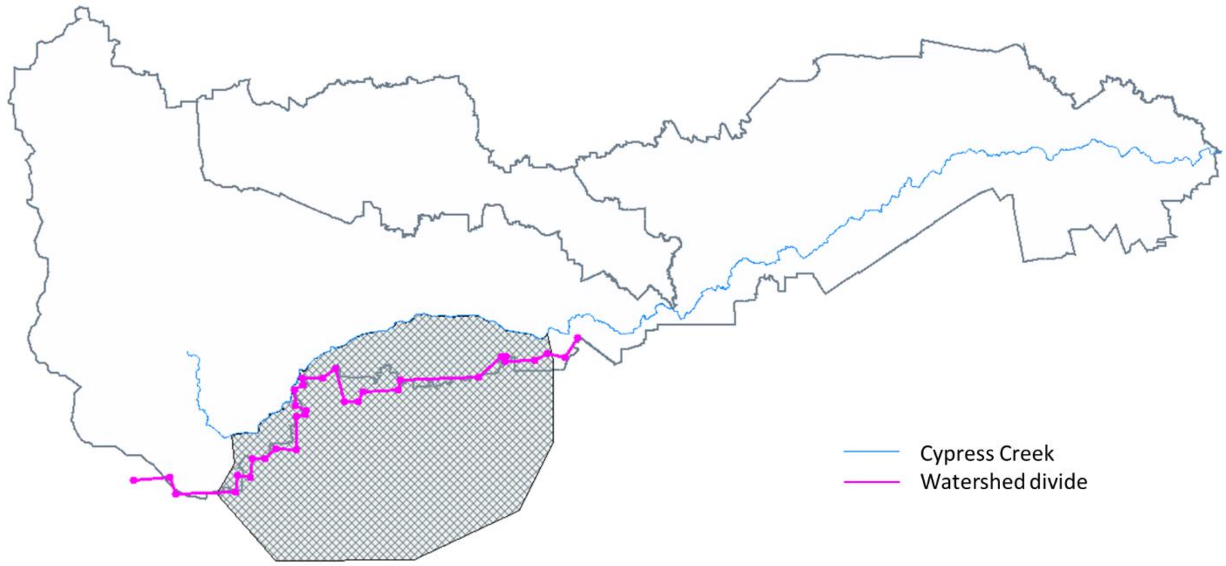
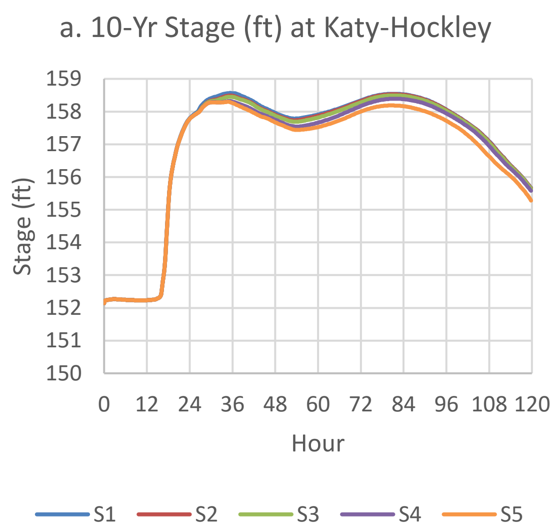
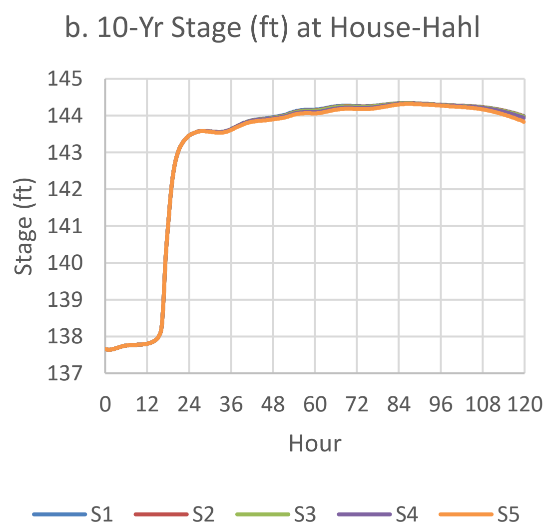
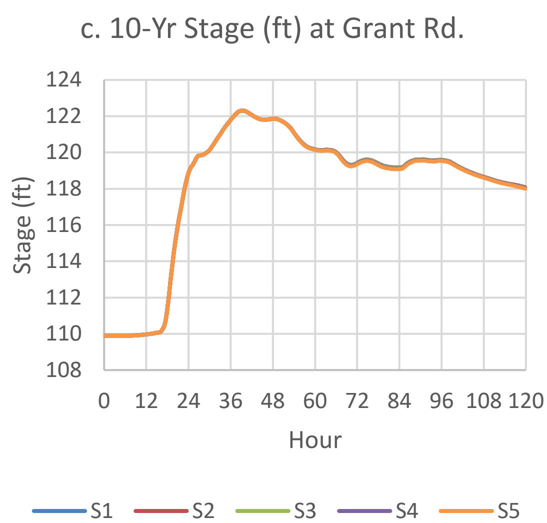



**Figure D-12: Cypress-Addicks watershed divide location**

### 10-Year





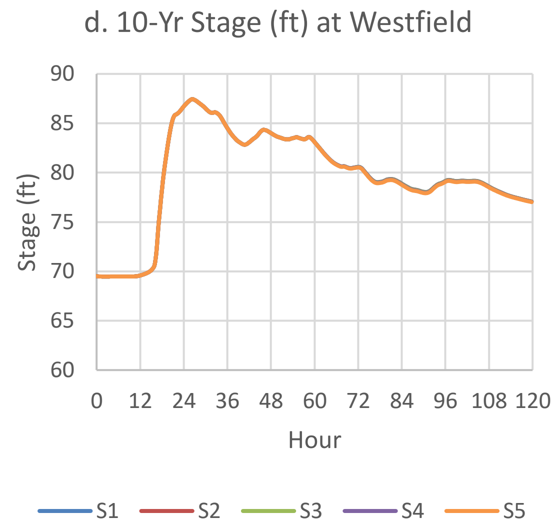
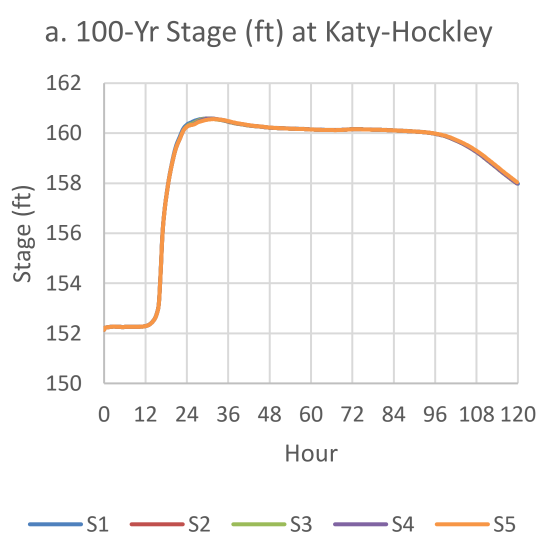



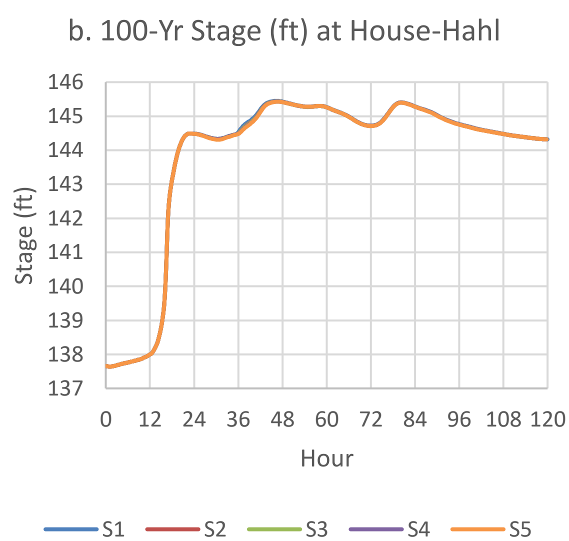

**Figure D-13a-d: Modeled 10-yr stage along Cypress Creek for Scenarios 1-5**

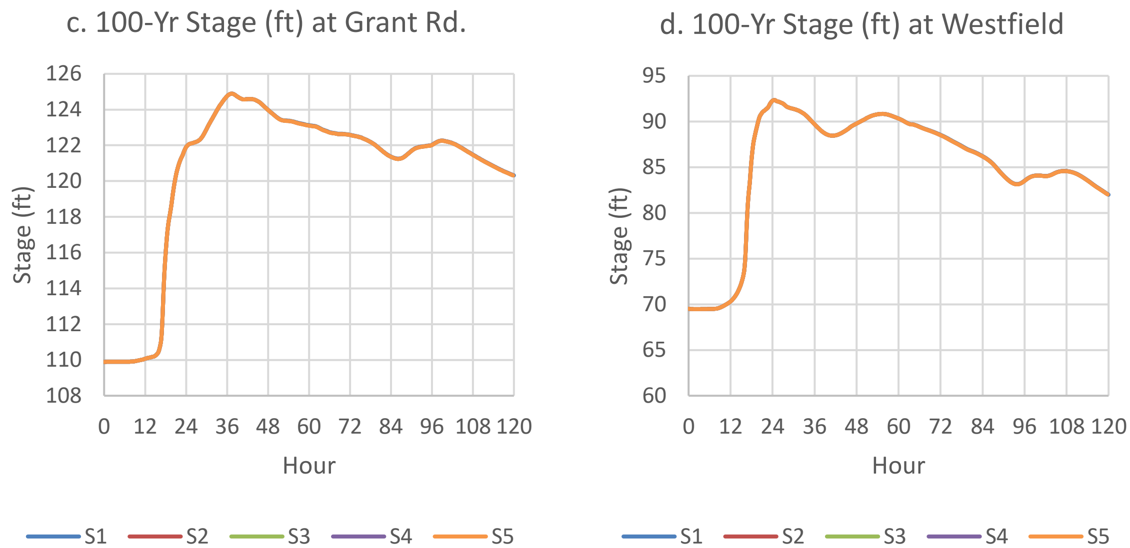
For the 10-year storm, the 1D/2D HEC-RAS results at the 4 USGS gage locations along Cypress Creek (Figures D-13a-d) are shown. Noticeable decreasing stages at Katy-Hockley from Scenario 1 (S1) through Scenario 5 (S5) can be seen, due to the increased infiltration storage and reduced runoff volume. However, little or no change is noticeable at the other gage locations. Since there were no overflows across the five modeled scenarios for the 10-yr storm, results along the watershed divide were not reported.

The 100-year storm results are shown in Figures D-14a-d. Little or no change is shown in the stages between the various scenarios at the 4 USGS gage locations.

**100-Year**

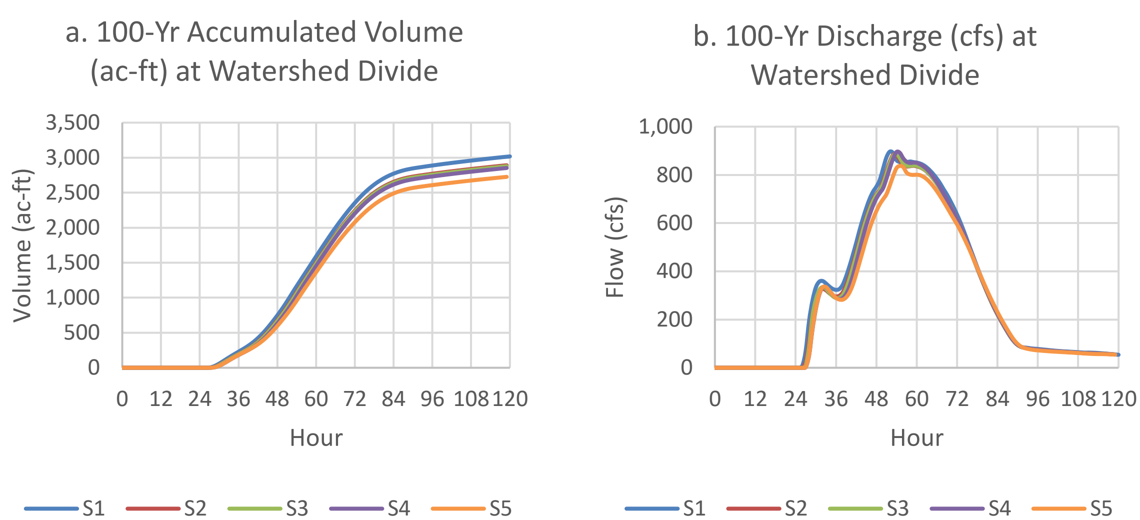





***Figures D-14a-d: Modeled 100yr stage along Cypress Creek for Scenarios 1-5***

Along the watershed divide however, noticeable reductions in both volume and discharge were observed (see Figures D-15a and b). The results for the 10-year and 100-year for the five scenarios are summarized in Tables D-1, D-2 and D-3.




**Figures D-15a-b: Modeled 100yr volume and discharge along watershed divide for Scenarios 1-5**

**Table D-1: Max Stage (ft) Comparison along Cypress Creek**

| Location | 10yr | | | | | 100yr | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S4 | S5 | S1 | S2 | S3 | S4 | S5 |
| Katy-Hockley | 158.57 | 158.53 | 158.49 | 158.39 | 158.3 | 160.59 | 160.58 | 160.58 | 160.58 | 160.57 |
| House-hahl | 144.34 | 144.34 | 144.34 | 144.33 | 144.32 | 145.45 | 145.43 | 145.43 | 145.43 | 145.43 |
| Grant Rd | 122.3 | 122.3 | 122.3 | 122.3 | 122.3 | 124.89 | 124.89 | 124.89 | 124.89 | 124.89 |
| Westfield | 87.44 | 87.44 | 87.44 | 87.44 | 87.44 | 92.34 | 92.34 | 92.34 | 92.34 | 92.34 |

**Table D-2: 100-Yr Storm Comparison for Scenarios 1-5 at Watershed Divide**

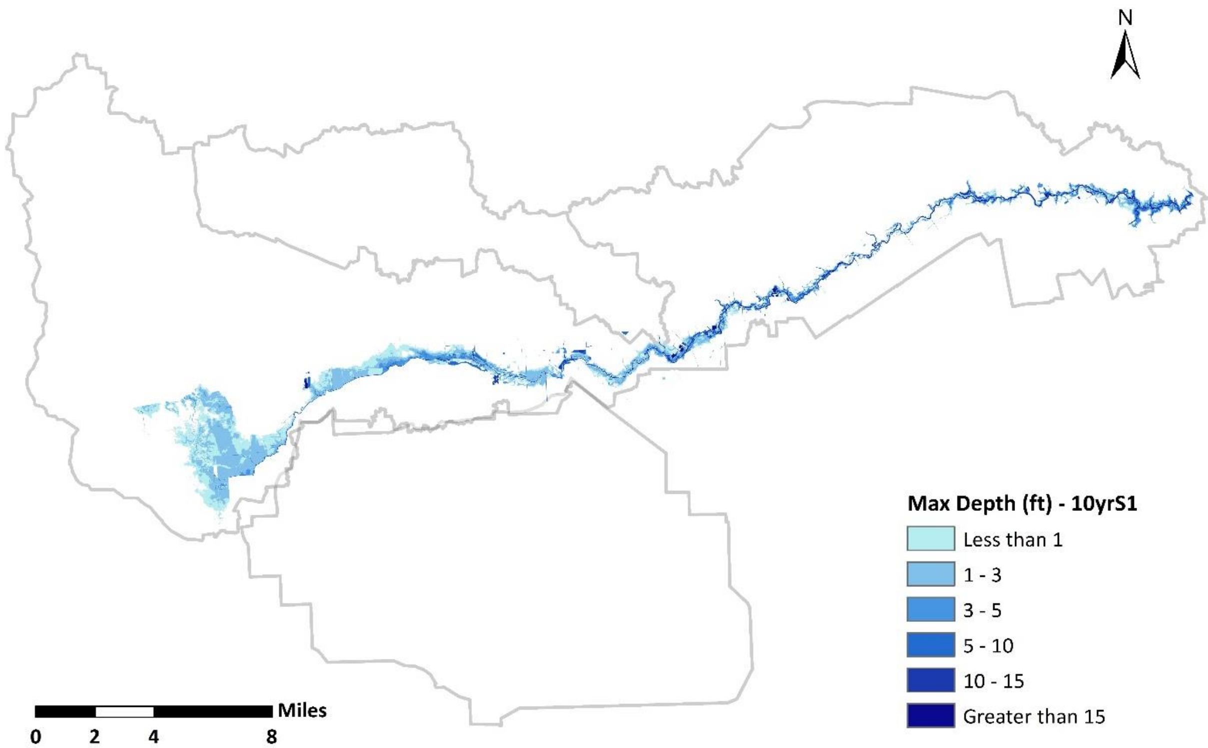
| | S1 | S2 | S3 | S4 | S5 |
|---|---|---|---|---|---|
| Volume (ac-ft) | 3018 | 2891 | 2877 | 2853 | 2726 |
| Peak flow (cfs) | 896 | 884 | 887 | 895 | 837 |

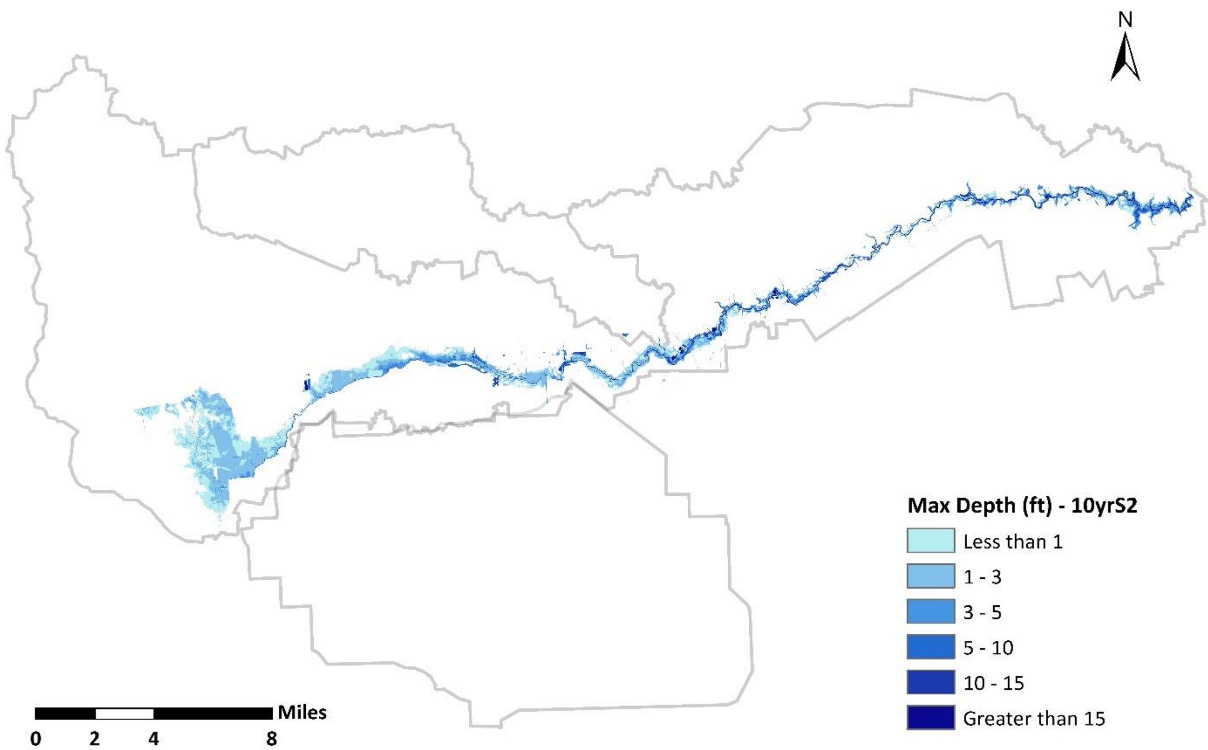
**Table D-3: % Reduction for 100-Yr Storm at Watershed Divide**

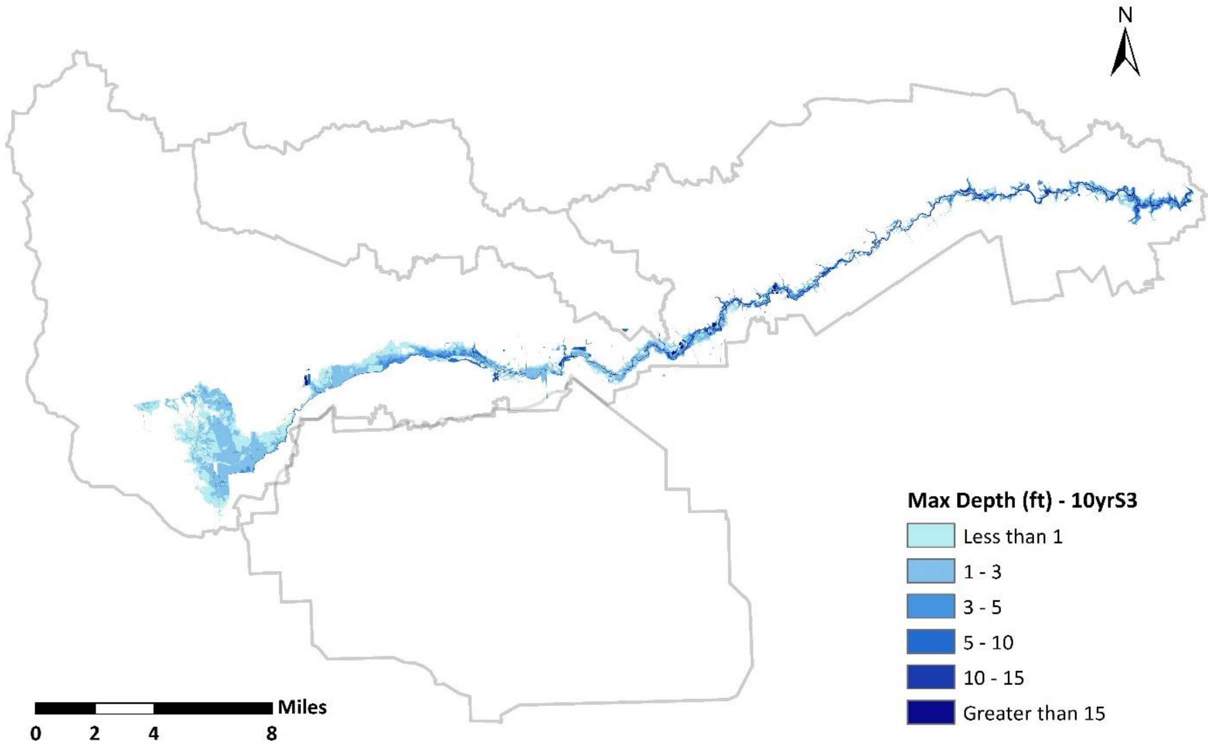
| | S1 | S2 | S3 | S4 | S5 |
|---|---|---|---|---|---|
| Volume | NA | 4.2% | 4.9% | 5.7% | 10.2% |
| Peak flow | NA | 1.4% | 1.1% | 0.2% | 6.6% |

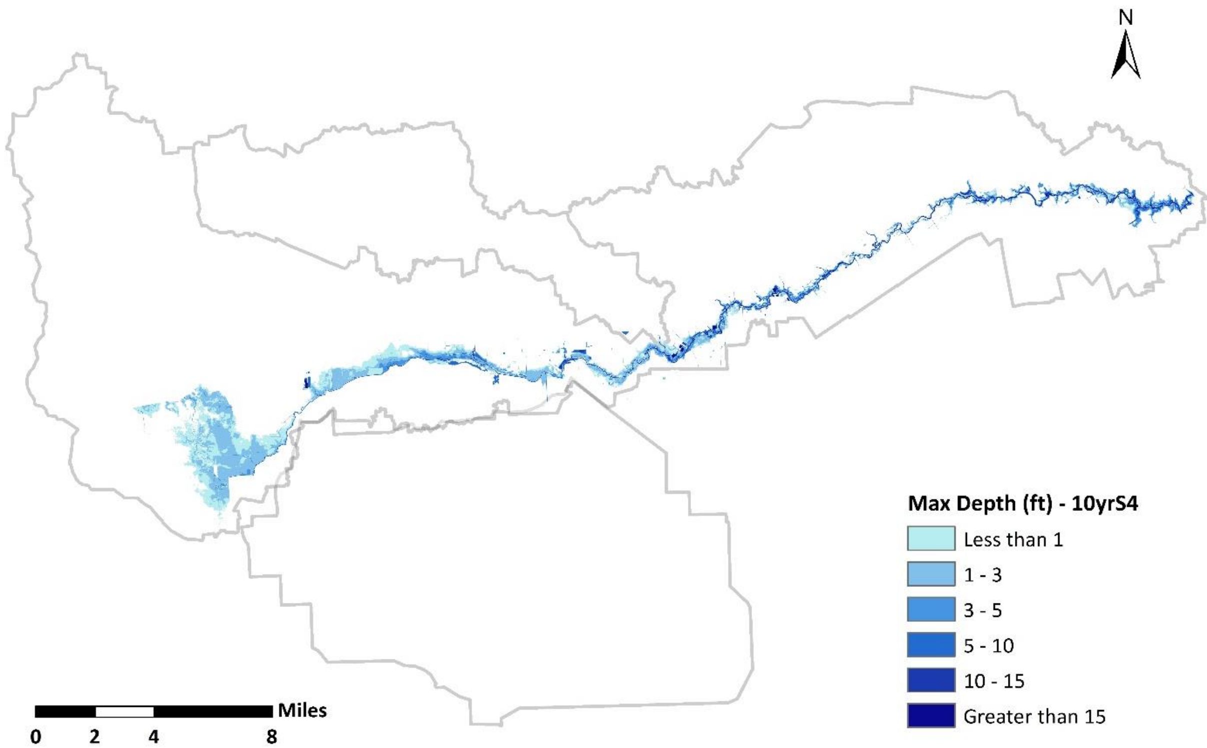
## Modeled Floodplains

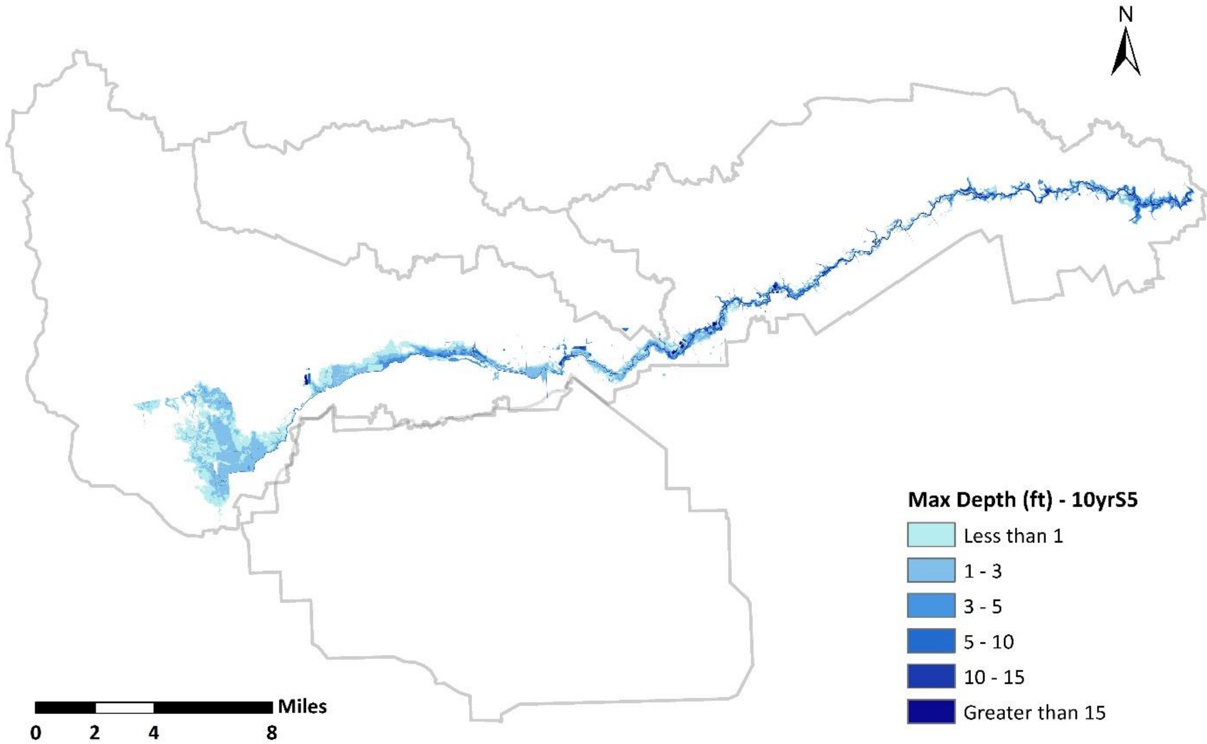
The resulting 10-year and 100-year floodplains based on the 1D/2D HEC-RAS model for Cypress Creek and its overflow area for the 5 scenarios are shown in the following Figure D-16.

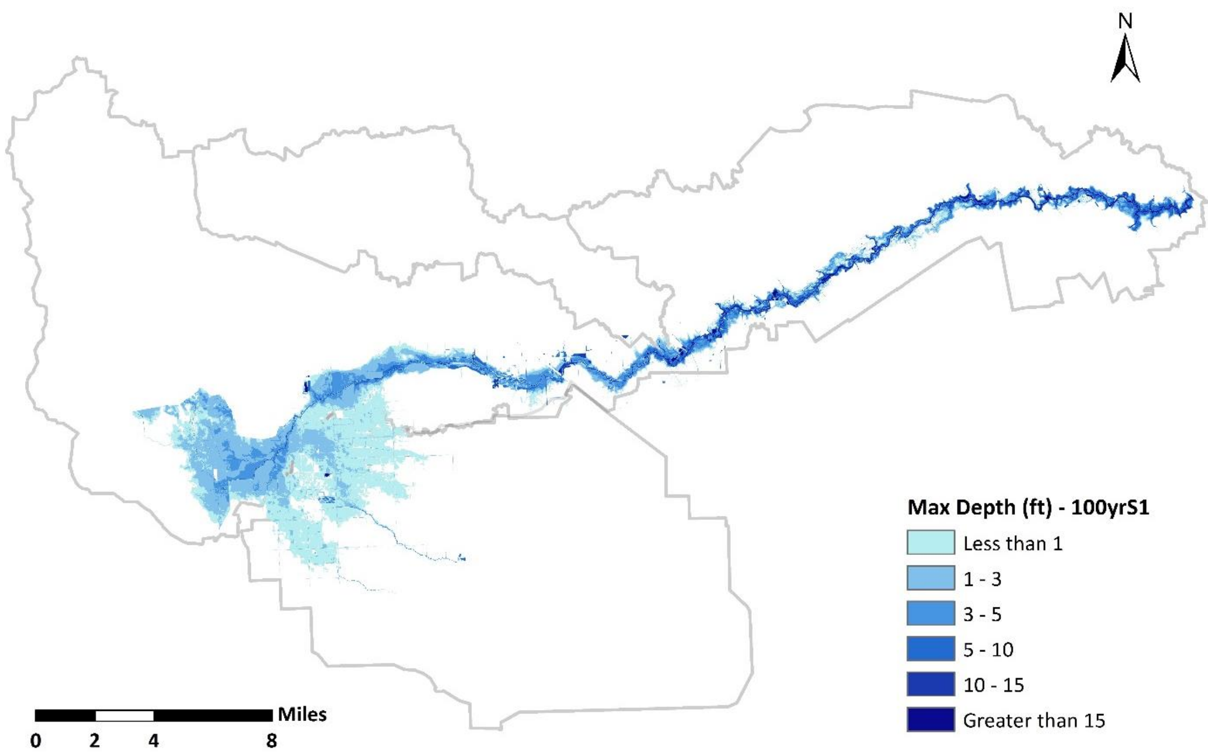

N
Max Depth (ft) - 10yrS1
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0 2 4 8

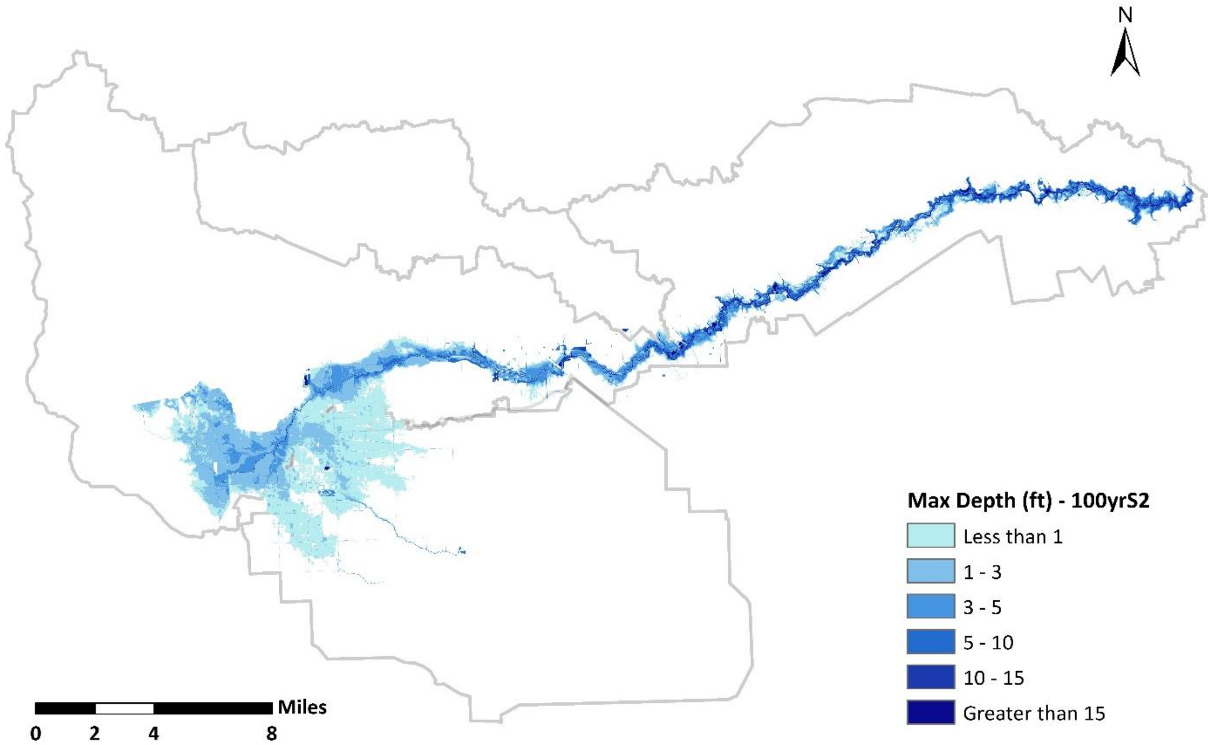

N
Max Depth (ft) - 10yrS2
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0 2 4 8

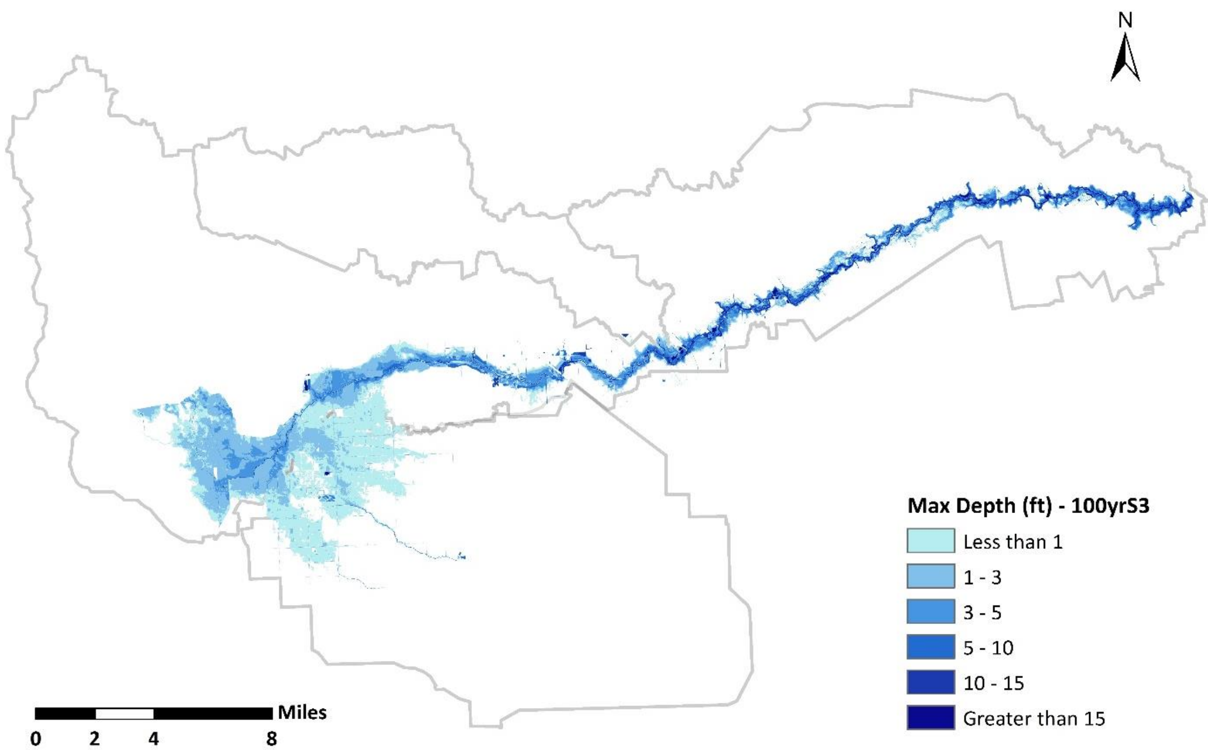

N
Max Depth (ft) - 10yrS3
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8

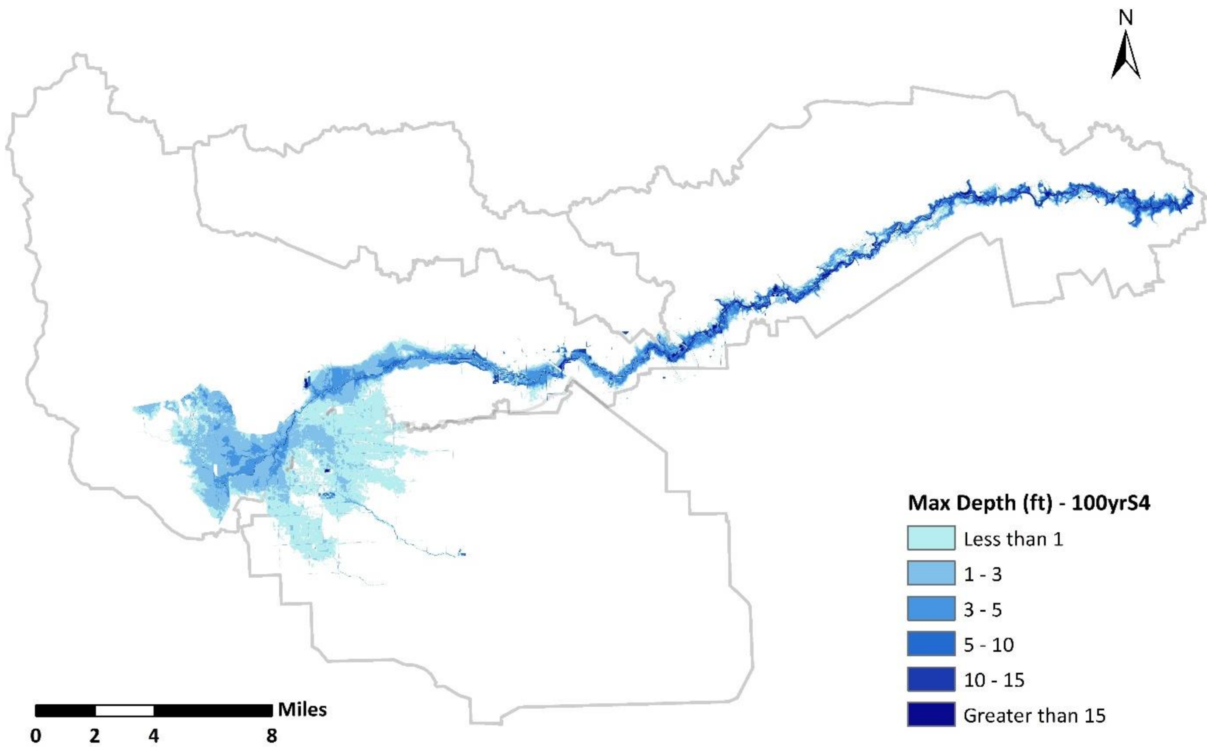

N
Max Depth (ft) - 10yrS4
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8


N
Max Depth (ft) - 10yrS5
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8


N
Max Depth (ft) - 100yrS1
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8


N
Max Depth (ft) - 100yrS2
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8


N
Max Depth (ft) - 100yrS3
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8



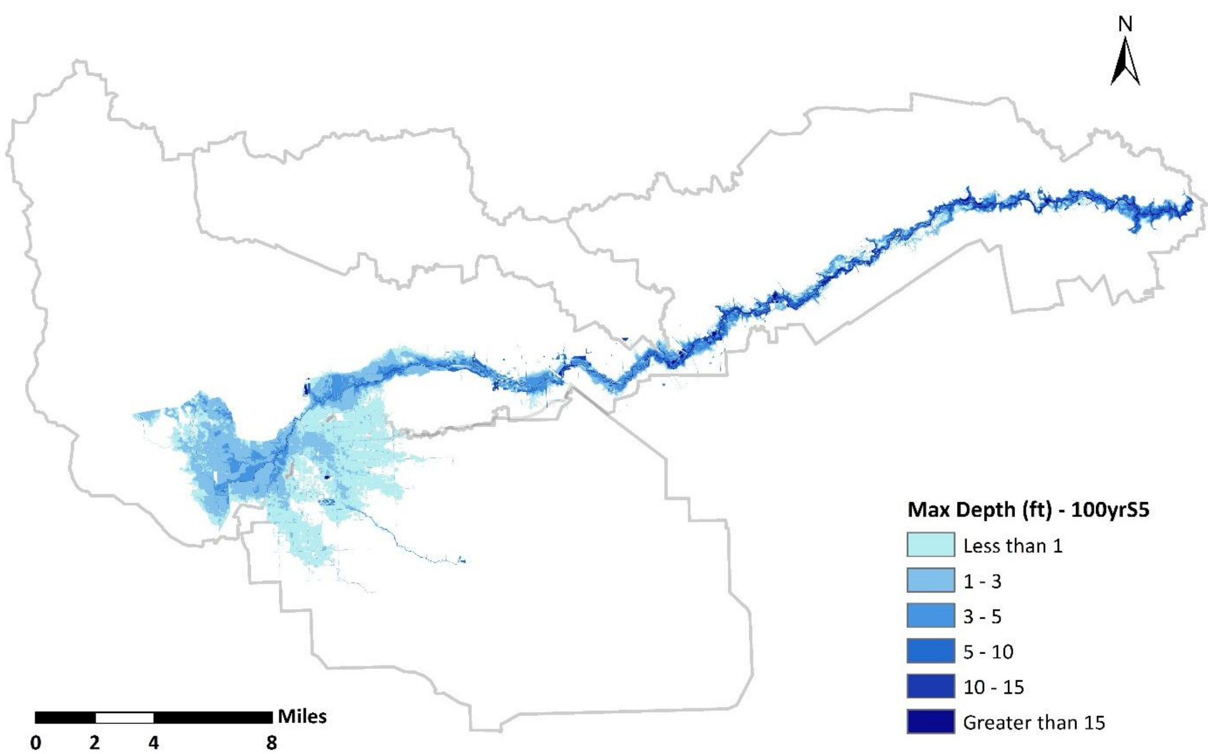
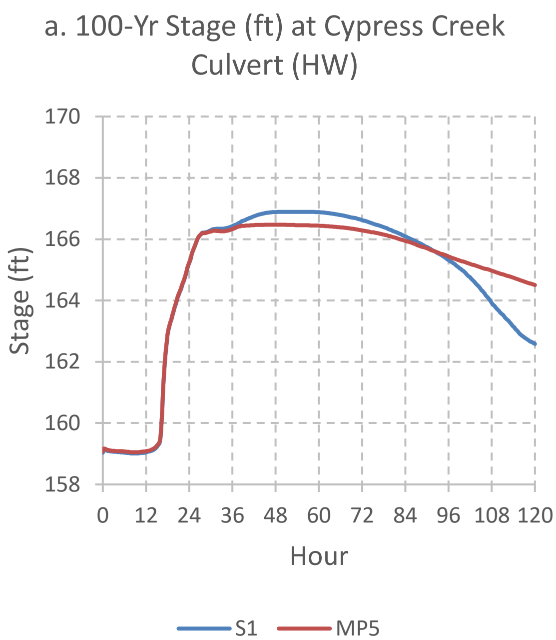
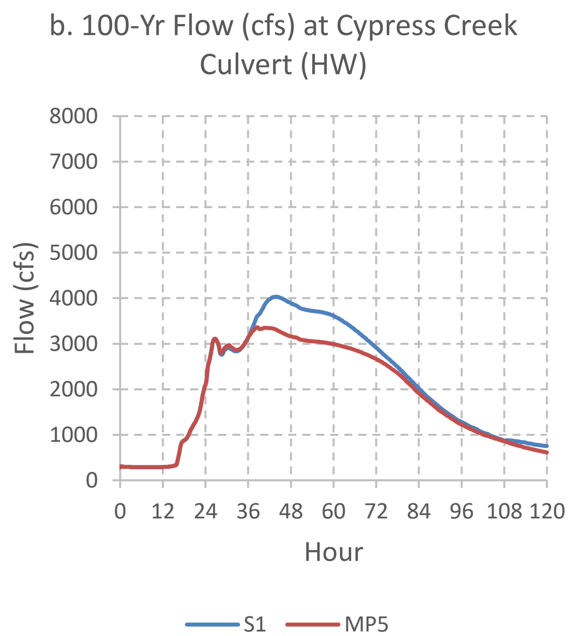



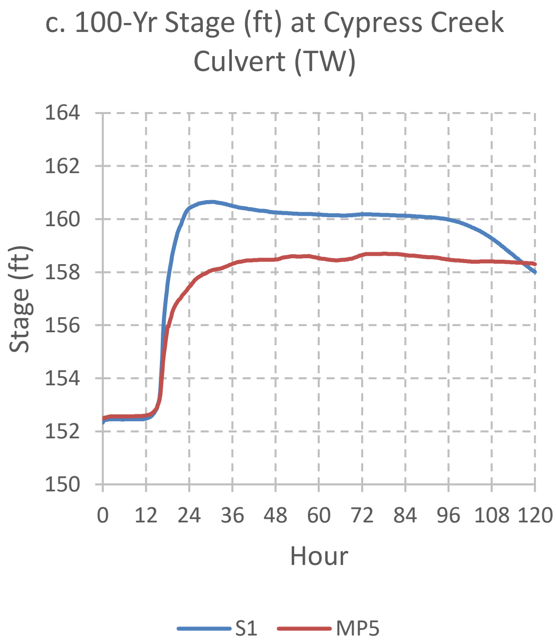

**Figure D-16. 10-yr and 100-yr Floodplains along Cypress Creek and its overflow area for Scenarios 1-5**

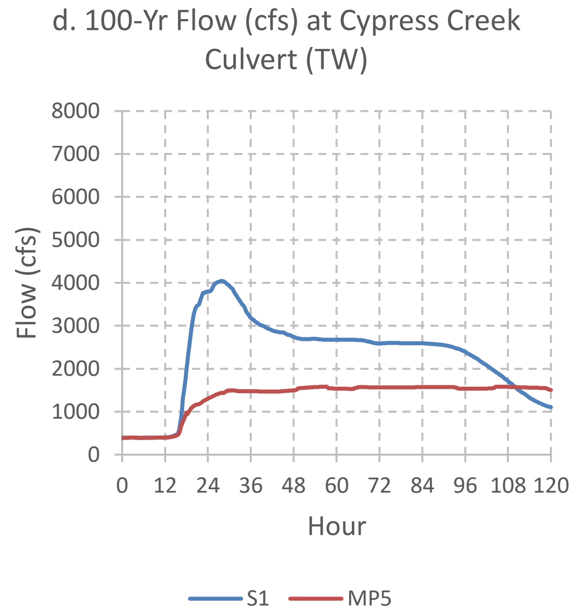
### Management Plan 5

To better understand the potential flood impacts of HCFCD's Management Plan 5, the 100-year and 500-year storms are simulated using the 1D/2D HEC-RAS model with this proposed berm/levee system in place. Stages and discharges at the two estimated outlet locations (i.e., Cypress Creek culvert and Bear Creek culvert) are calculated by the model (see Figures D-16a-d and D-17a-d for 100-yr results and Figures D-18a-d and D-19a-d for 500-yr results). Additionally, volume, discharge and maximum water depth along the watershed divide are also calculated for Plan 5 (MP5) and compared to the S1 (Baseline) scenario.

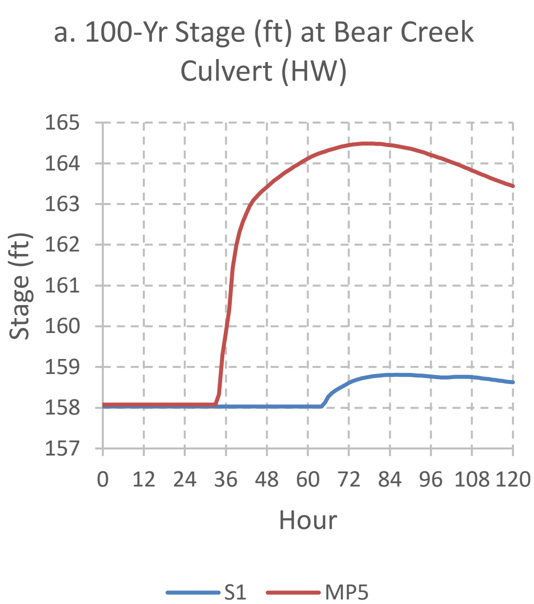


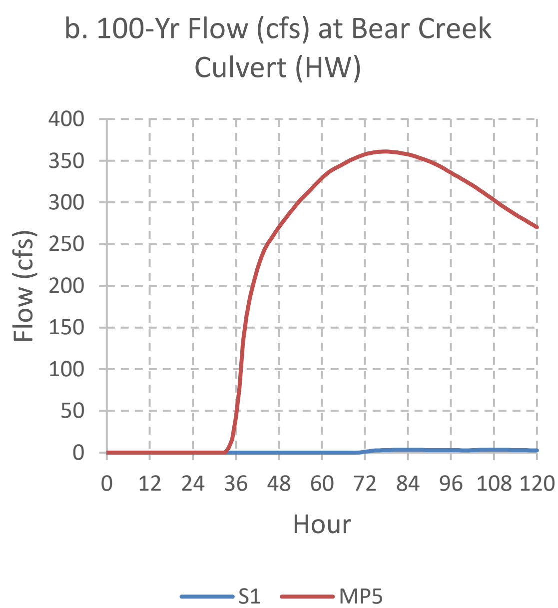



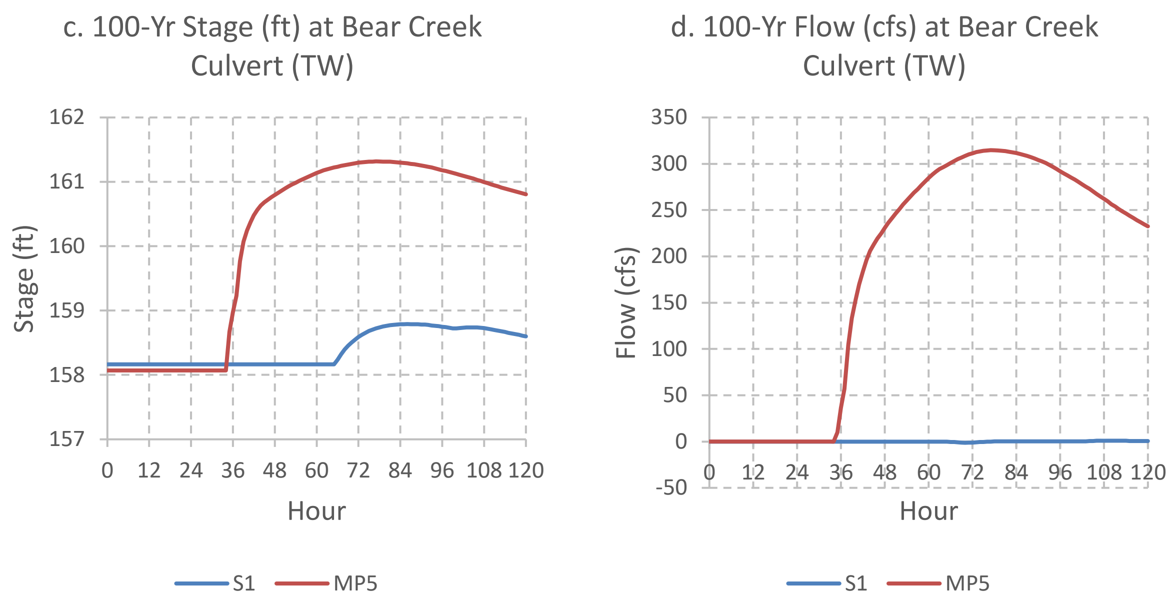


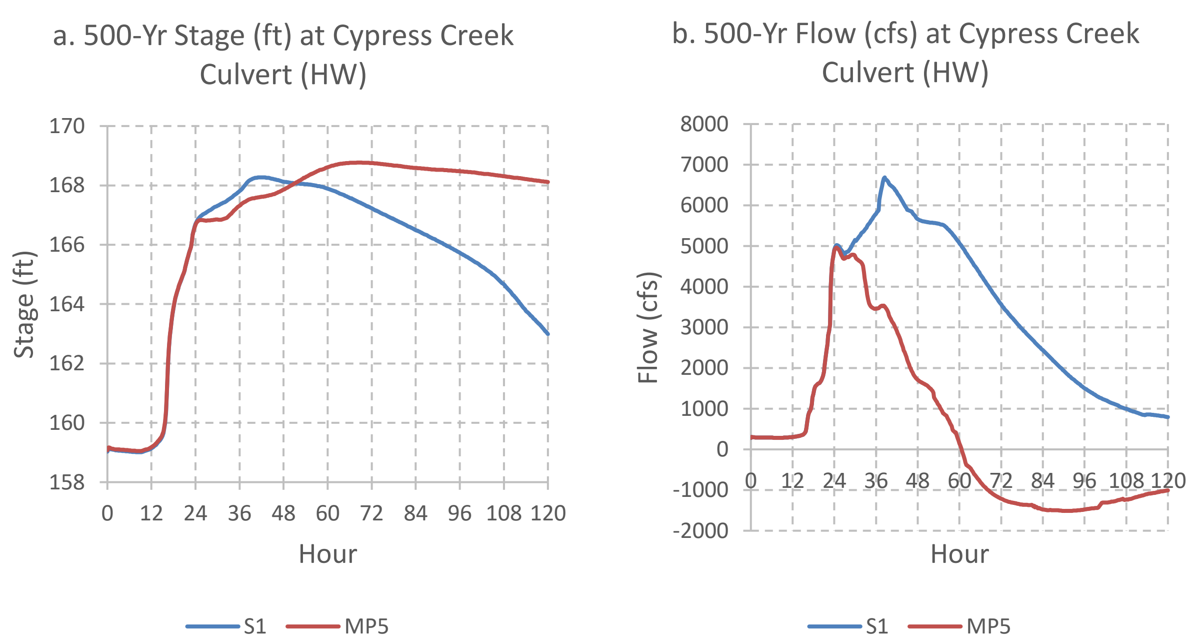

**Figures D-16a-d: Modeled 100yr stage and flow at Cypress Creek Culvert (HW: headwater, TW: tailwater)**

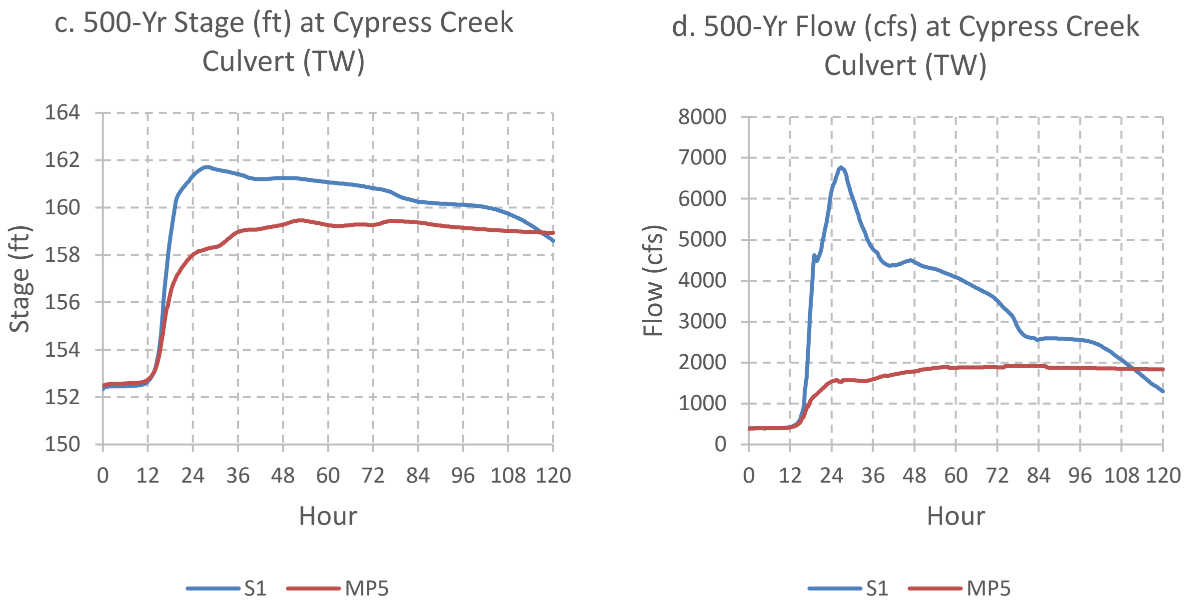


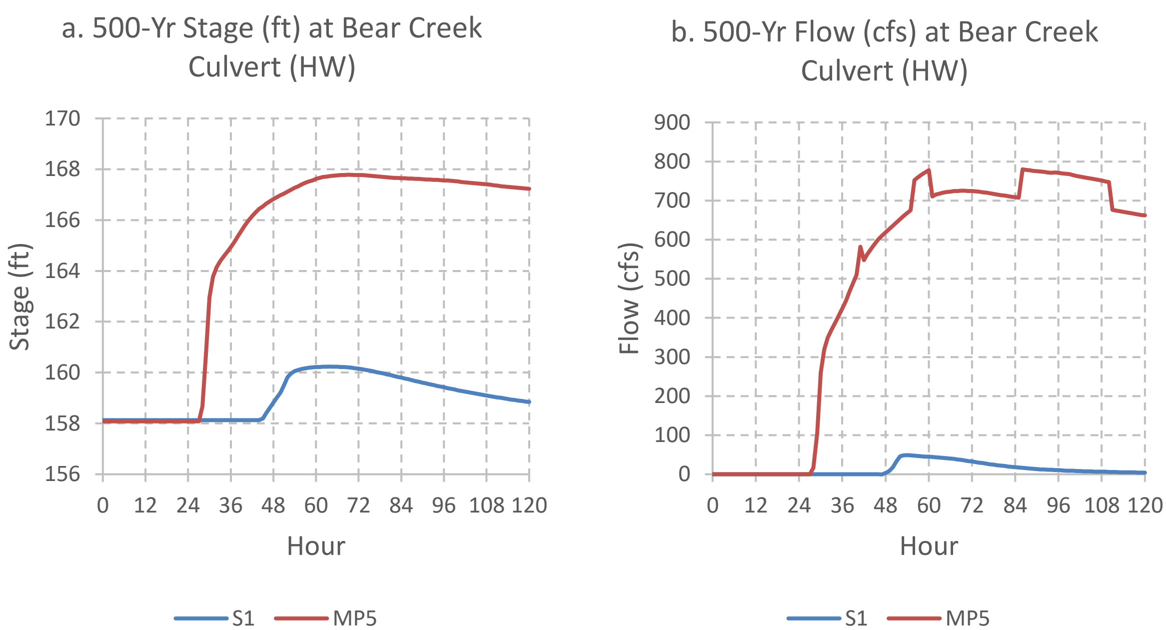


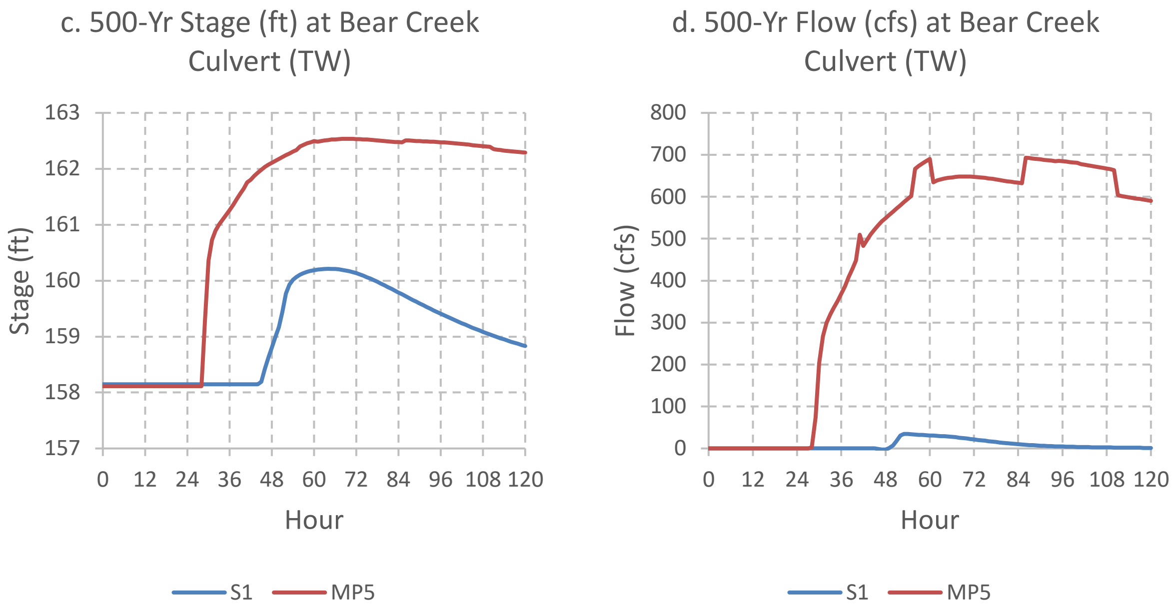

**Figures D-17a-d: Modeled 100-yr stage and flow at Bear Creek Culvert (HW: headwater, TW: tailwater)**



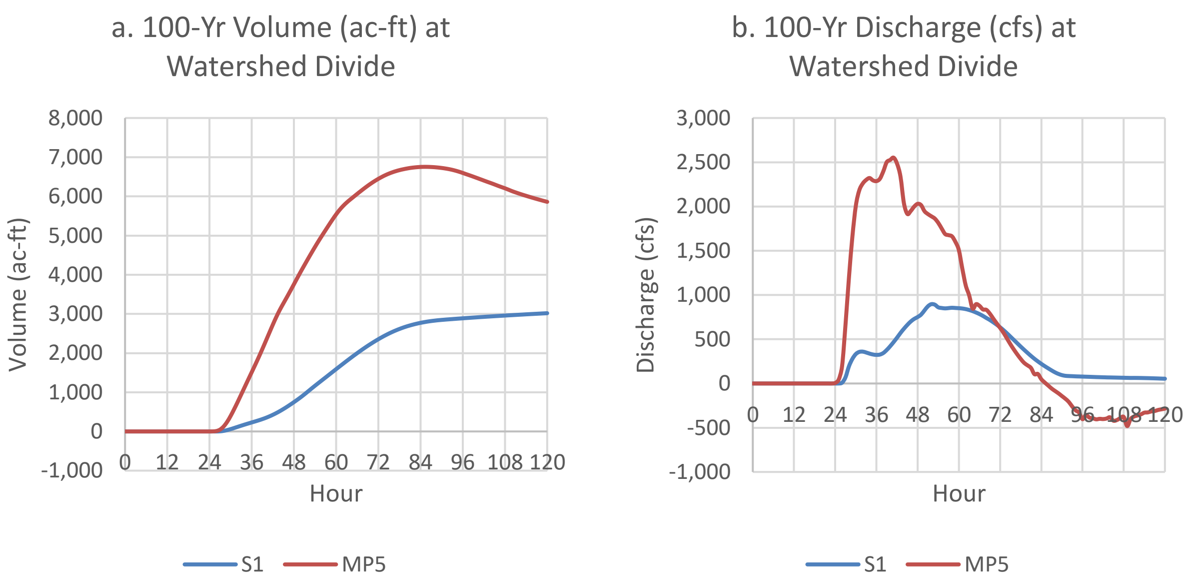


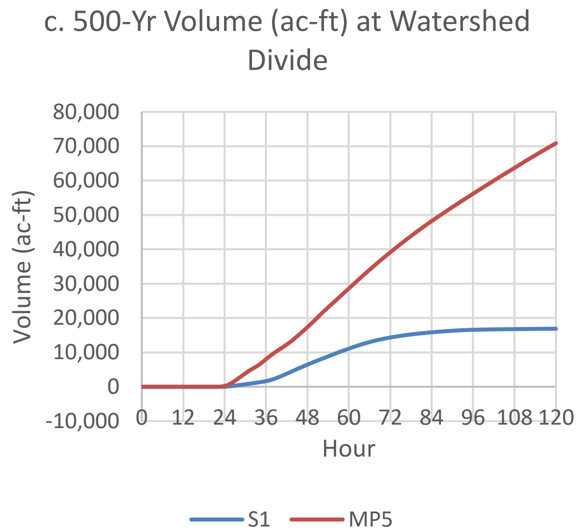

**Figures D-18a-d: Modeled 500yr stage and flow at Cypress Creek Culvert (HW: headwater, TW: tailwater)**

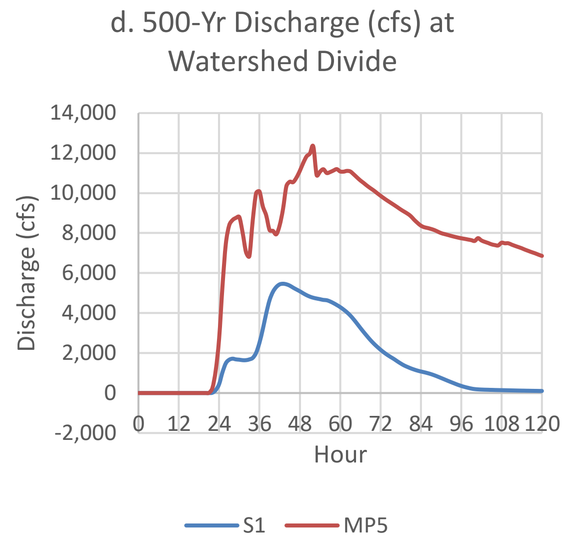





**Figures D-19a-d: Modeled 500yr stage and flow at Bear Creek Culvert (HW: headwater, TW: tailwater)**






**Figures D-20a-d: Modeled volume and flow at watershed divide**

As shown in Table D-4, volume and peak flows between S1 and Plan 5 are compared for the 100-yr and 500-yr storms. The Tax Day 2016 results are also included for reference, in which they showed that the event was between a 100-yr and 500-yr storm. Figure D-21 compares the maximum depth for the 100-yr, 500-yr and Tax Day 2016 storms for the Baseline Scenario 1 versus Plan 5. Maximum water depth along the watershed divide (station number locations are shown in Figure D-22) and the maximum depth comparisons between S1 and MP5 for the 100-year and 500-year storm events are shown below in Figures D-23a-d and D-24a-d.

**Table D-4: Scenarios S1 vs Plan 5 Volume and Flow at Watershed Divide for 100- and 500-yr and Tax Day 2016**

| | 100yr | | 500yr | | Tax16 |
|---|---|---|---|---|---|
| | S1 | MP5 | S1 | MP5 | |
| Volume (ac-ft) | 3018 | 6753 | 16899 | 70857 | 8707 |
| Peak flow (cfs) | 896 | 2552 | 5465 | 12330 | 3042 |

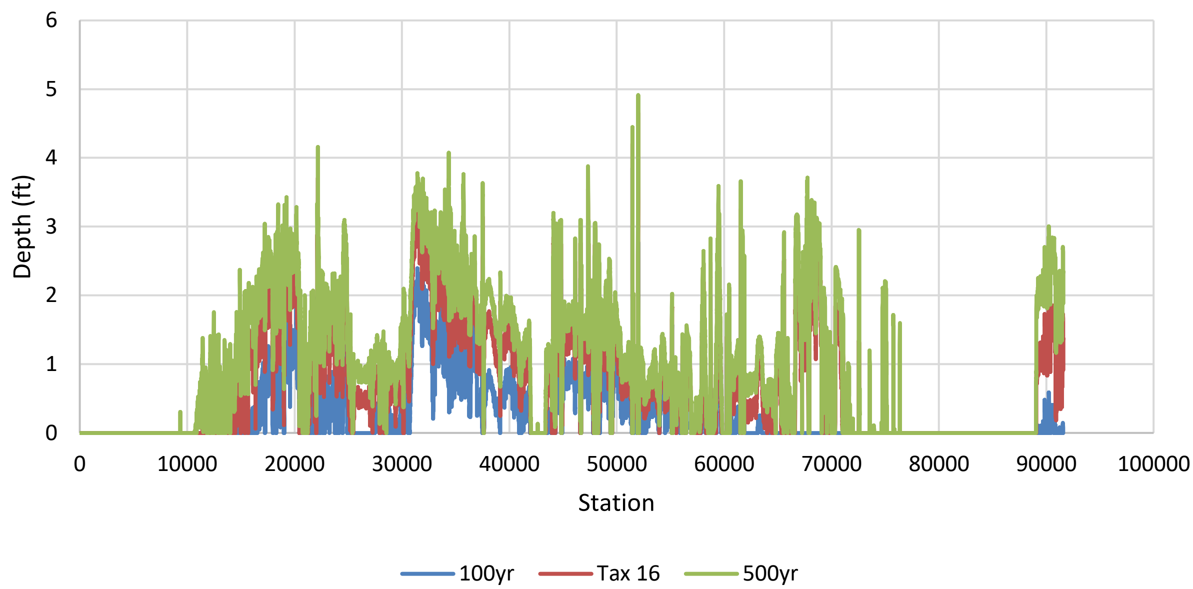



**Figure D-21: Max Depth Comparison along Watershed Divide under S1 Scenario**

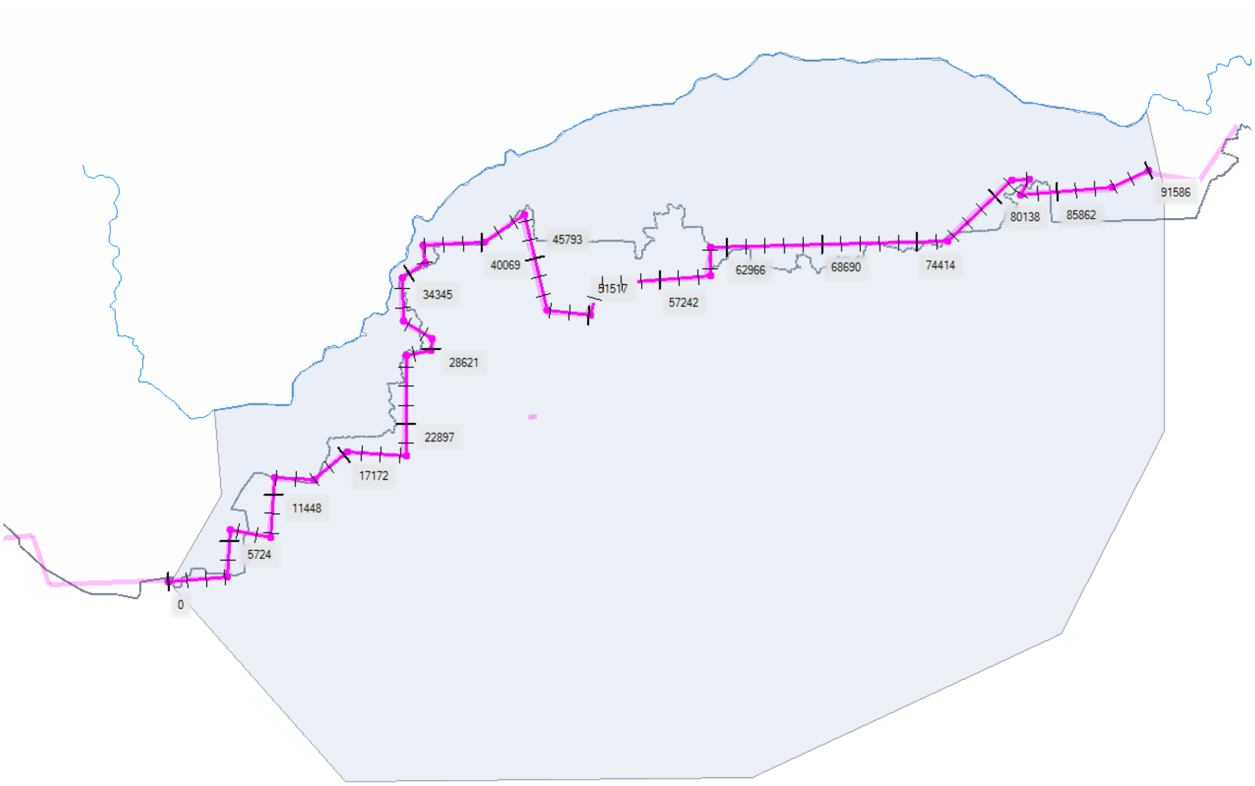
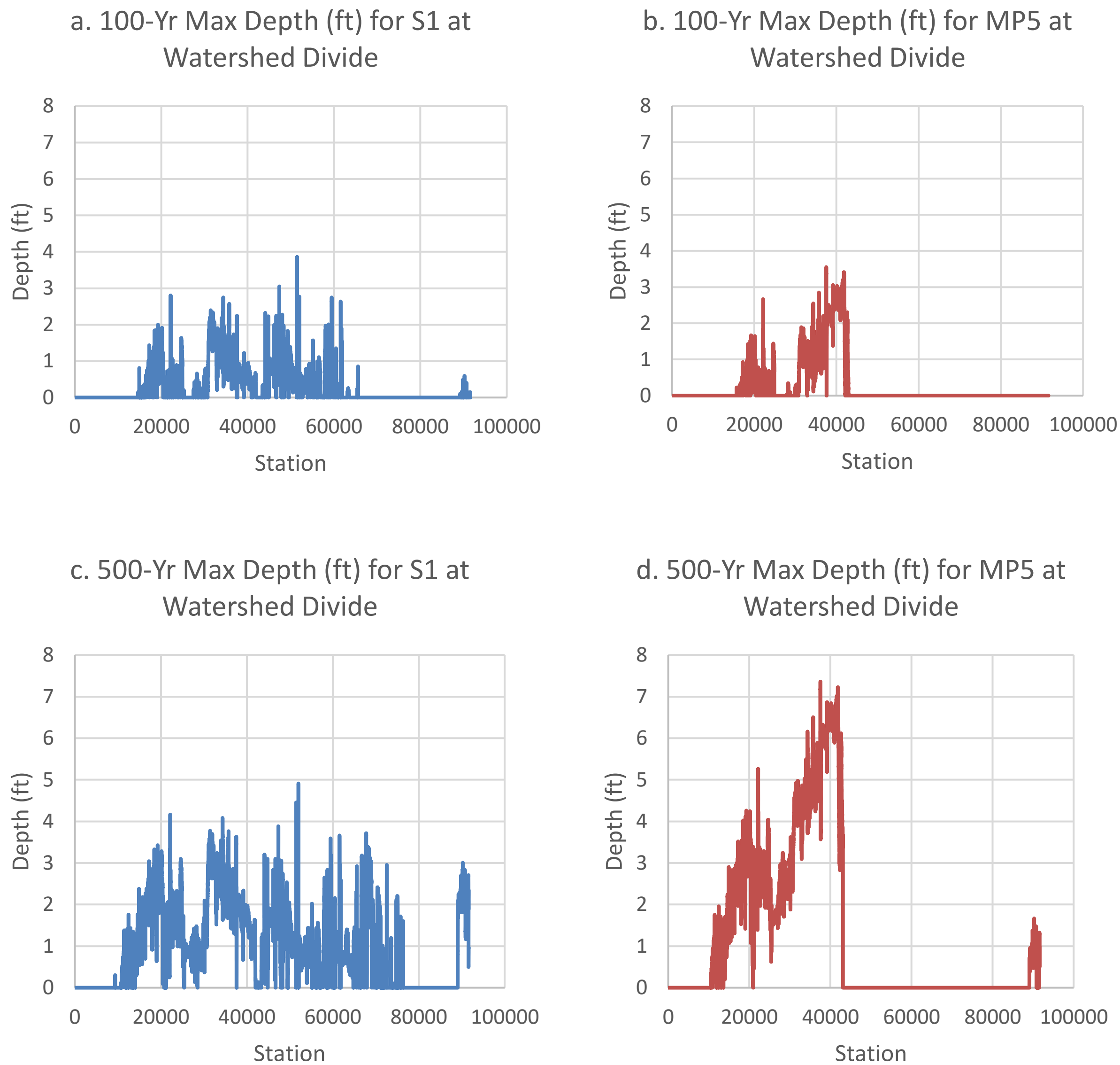
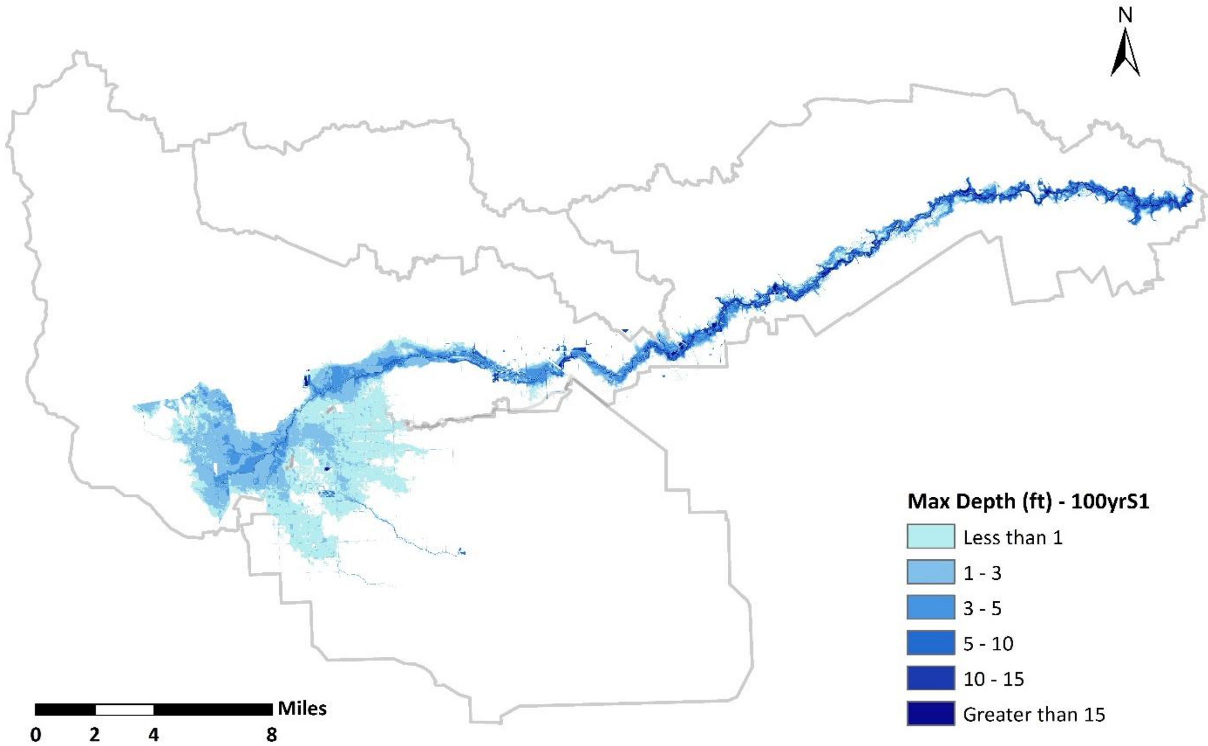
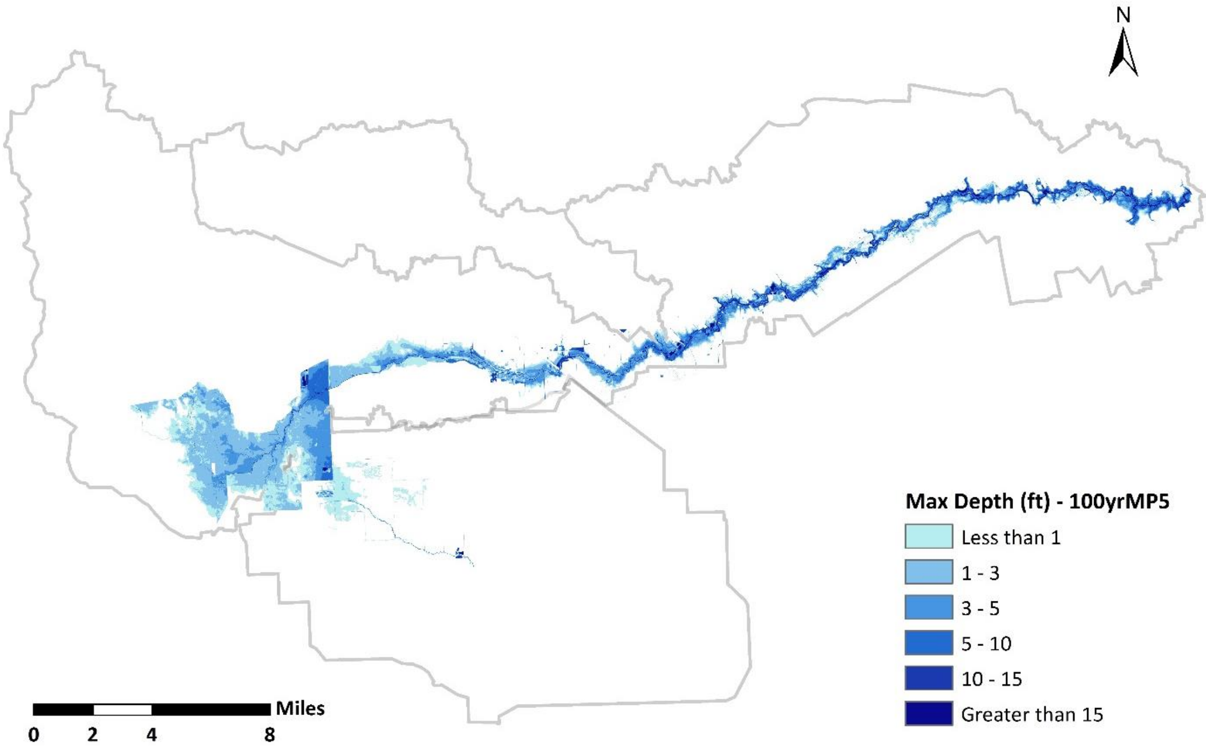


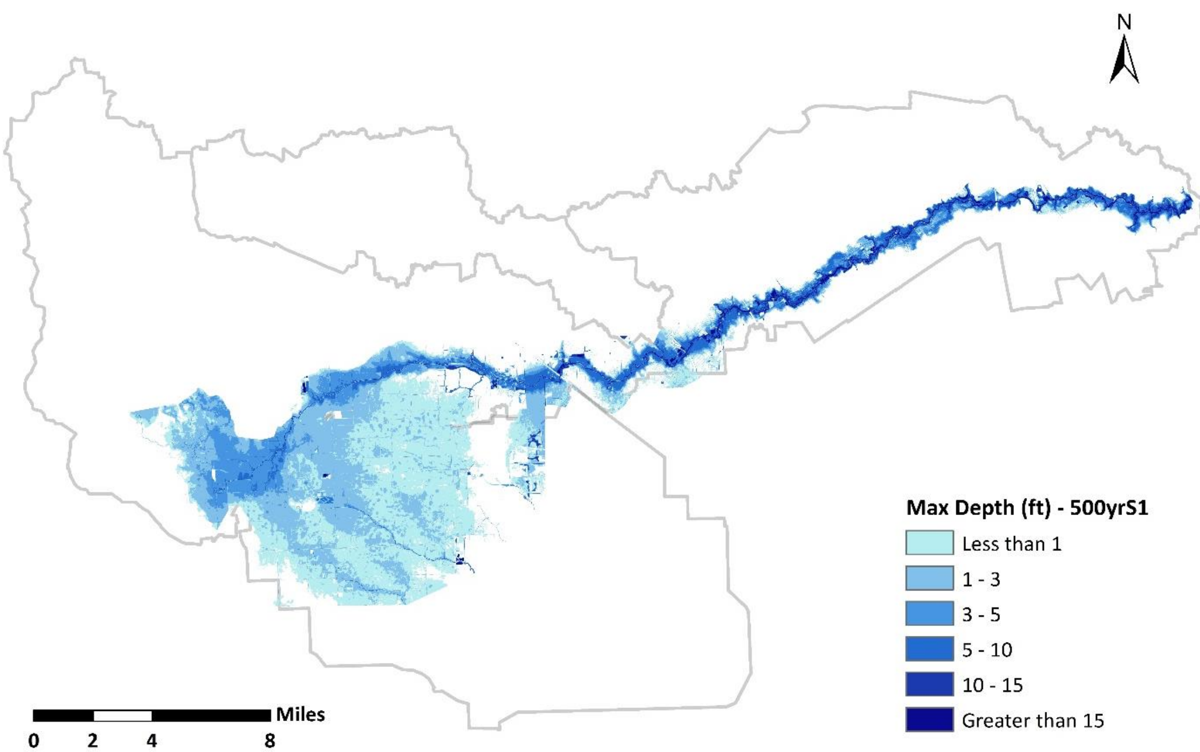

**Figure D-22: Watershed Divide Schematic with Station Numbers**

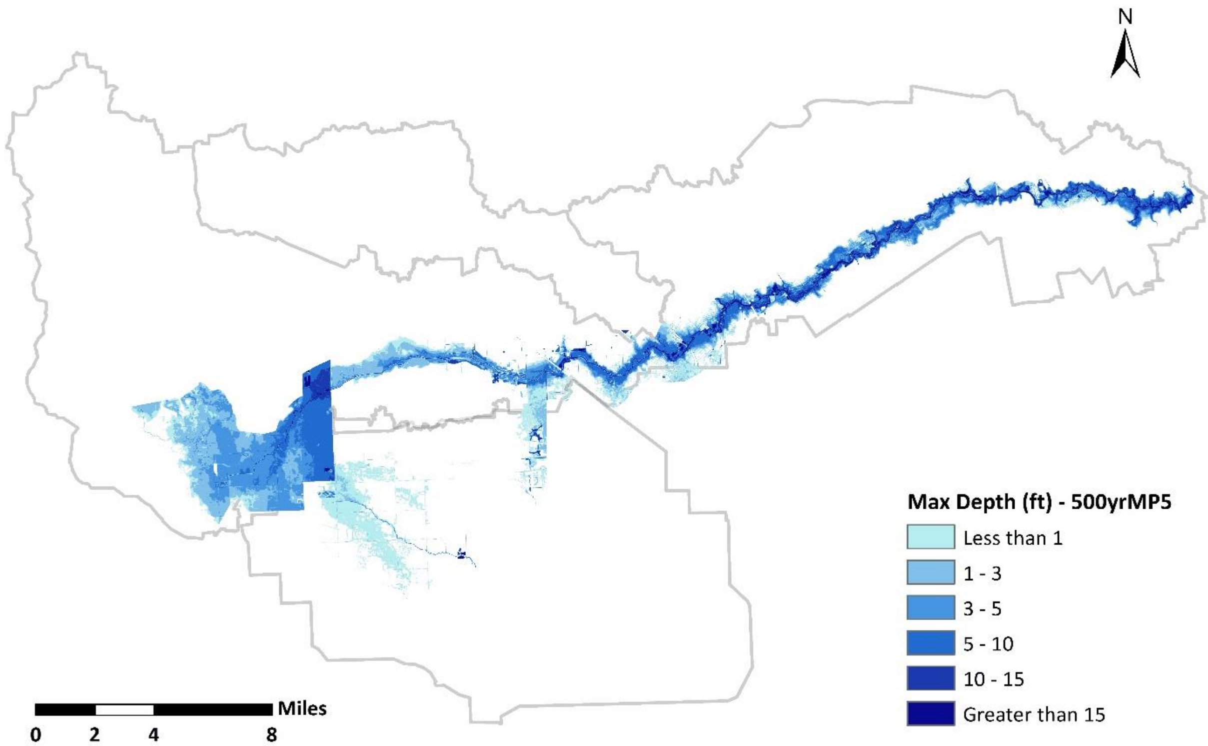



**Figures D-23a-d: Max depth of 100-yr and 500-yr storms along watershed divide for S1 and MP5 scenarios**


N
Max Depth (ft) - 100yrS1
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0
2
4
8


N
Max Depth (ft) - 100yrMP5
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0 2 4 8


N
Max Depth (ft) - 500yrS1
Less than 1
1 - 3
3 - 5
5 - 10
10 - 15
Greater than 15
Miles
0 2 4 8




**Figures D-24a-d: Maximum depth for 100-yr and 500-yr along Cypress Creek and overflow area for S1 and MP5 scenarios**

## Appendix E. Hydrologic Modeling and Detention Storage

An extensive sensitivity analysis was performed to analyze the impact of vegetative roughness in the watershed. The Manning's coefficient of 100,000 acres in Upper Cypress Creek (

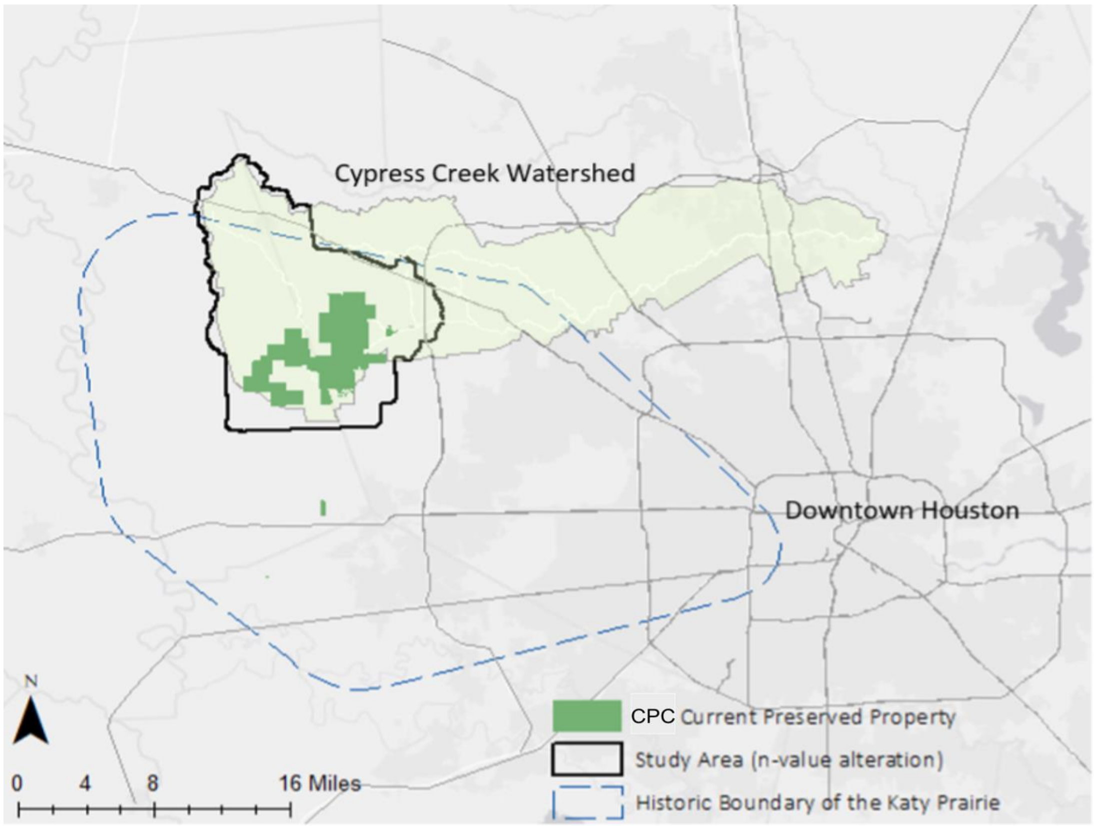



Figure E-1.) was adjusted from the associated NLCD 2016 land use classification roughness values to represent a scenario with altered land use classification (Manning's of 0.1 representing development, and Manning's of 0.6 representing complete prairie restoration (Weltz and Arslan 1992). The 100,000-acre area was chosen because it encompasses the catchment area for all rainfall that would enter and leave the current CPC property, and it was identified in a previous study conducted by the SSPEED Center and AES Inc. as a site for potential prairie restoration and expansion (Apfelbaum et al. 2018).

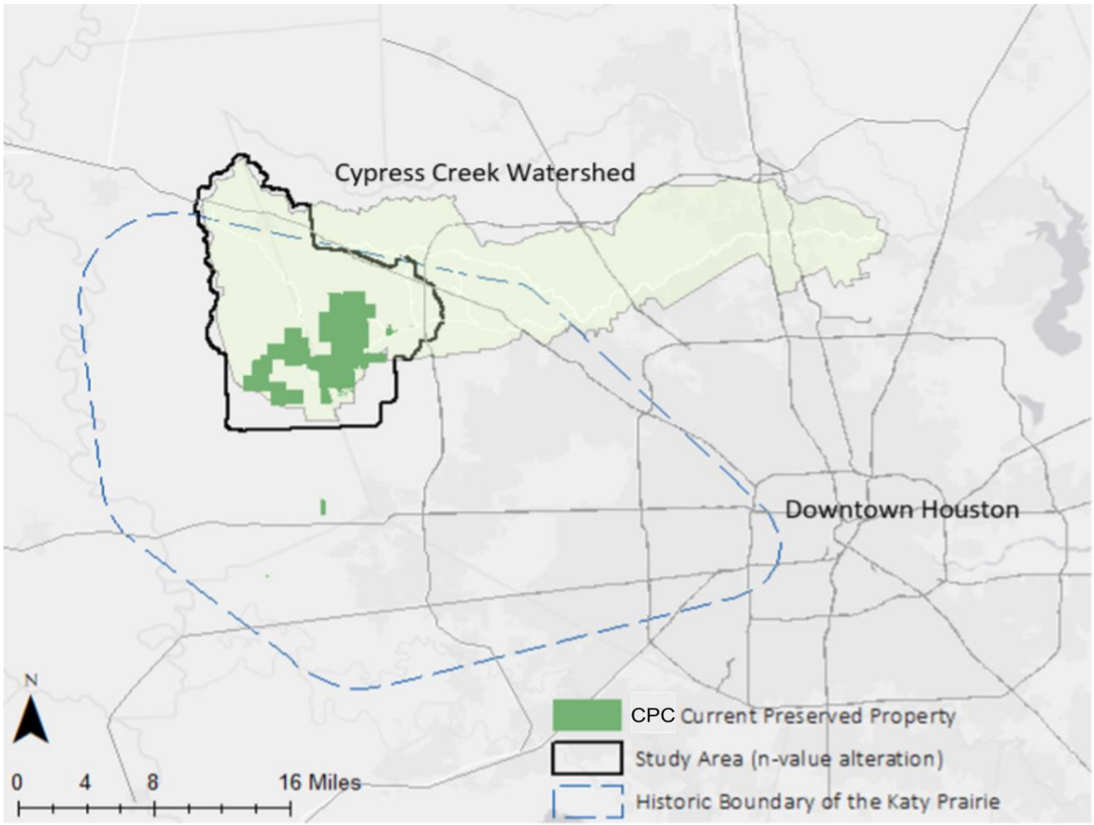


Figure E-1. Study Area with 100,000 acres for Roughness Evaluation

Evaluation of model response at over fifty watch points along Cypress Creek, Little Cypress Creek and tributaries showed significant reduction in both peak flow volume and timing under conditions of increasing Manning's roughness. In evaluating the model under four storm scenarios, results showed prairie vegetation would generally have a more dominant impact during smaller volume storms (2-year or 10-year storms) than a 0.2% storm event (Figure E-2.) . It should also be noted from Figure 2 (below) that within the region of n-value alteration, reduction in peak flow was loosely inversely correlated to catchment size ($R^2 = 0.58$ (100-yr)). This behavior correlation, however, is weaker when including assessment points downstream or outside the areal extent of the n-value alteration ($R^2=0.37$ (100-yr)). These results are consistent with field studies on prairie restoration sites, where it has been repeatedly noted that overall reduction in peak flow is highly dependent on location of restored prairie in comparison to the catchment of interest (Cowdery et al. 2019; Schilling and Drobney 2014).

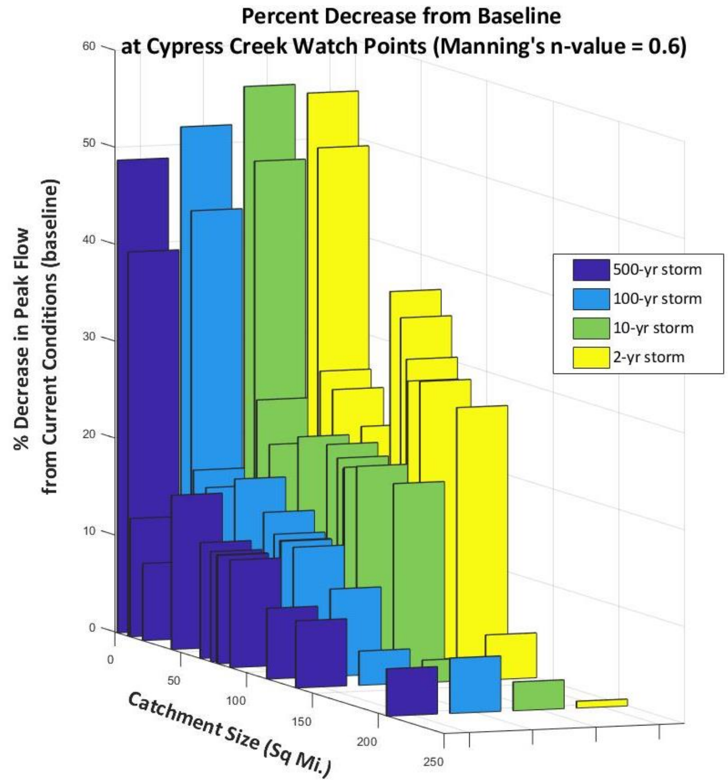



Figure E-2. Percent change in Peak Flow with Manning's Roughness of 0.6 versus Current Conditions

In addition, the impact of overflow from Cypress Creek in the middle of current KPC property contributed to variability in peak flow reduction at points along the main channel within the estimated overflow and downstream. The variability is thought to have been caused by the stage-discharge curves used to represent the overflow in the *Vflo®®* model. The variability could suggest that some of the reduction in peak flow observed in these areas is muted or negligible due to overflow. Because the overflow volume, timing and location along Cypress Creek is not fully understood, the results of this study are most impactful without considering the overflow phenomenon, as this response would be more reflective of other coastal prairie watersheds. The detention storage results in the following section, and the water surface elevation (WSEL) decrease in Table E -1 are derived *without* considering overflow. Due to this overflow phenomenon in the watershed, however, results from this study should be considered relative for the Katy Prairie region and could vary depending on the timing, distribution and intensity of a real storm event.

The peak flows evaluated in *Vflo®®* for each storm scenario, and each n-value condition, were input into a steady flow file in 1D HEC-RAS to evaluate how change in peak flow translated to change in water surface elevation in the channel. The results are summarized in Table E -1 (100-yr Storm, n=0.6 restoration scenario) for the watch points corresponding to Figure E-3.

| 24-hour, 100-yr Atlas 14 Storm | | | | | |
|---|---|---|---|---|---|
| Location | Mathis Road (1) | Sharp Road (2) | Katy-Hockley (3) | House-Hahl (4) | Grant Road (5) |
| Decrease from baseline (current conditions) (ft) | 0.25 | 0.6 | 0.85 | 0.57 | 0.35 |

Table E -1. Decrease in Water Surface Elevation Along Main Cypress Creek (Restoration Scenario)

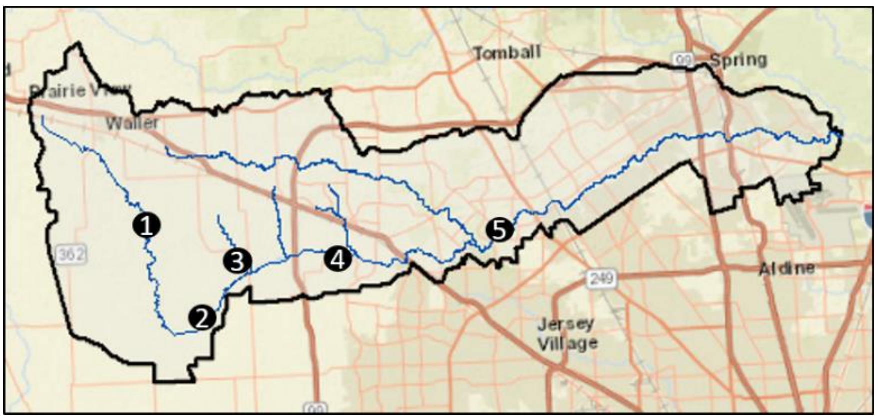



Figure E-3. Points Corresponding to WSEL Comparison

The change in WSEL in Cypress Creek after increasing the overland Manning's roughness is minimal, but large enough to be significant with respect to flooding. Further investigation of this is suggested as future work for this study, including evaluating the reduction in areal extent of the floodplain or number of parcels removed from the downstream floodplain in restoration scenarios. However, corresponding to the modeled change in peak flow, the reduction in WSEL decreases moving further downstream from the zone of n-value alteration. Current development extent is limited westward until near the confluence of Little Cypress Creek, which indicates the impact of upstream prairie restoration on removing current development from the floodplain may be minimal. The next chapter will continue the discussion on the spatial variance in magnitude of runoff-reduction both reaching the channel and in overland catchments observed in the modeling results.

### Detention Storage

Detention ponds are designed for the purpose of detaining stormwater runoff over a period of time (typically 24-72 hours) before discharging the water off-site or downstream (Bedient et al. 2018). In theory, detention storage is required for new development to prevent generated rainfall-runoff from exceeding rates of pre-development conditions. On-site detention requirements for Harris County have been updated to accommodate rainfall increases from 2018 NOAA Atlas 14 and are summarized in Table 2 along with the general method from which they are derived. The rate at which runoff is allowed to leave the property dictates the inflow, outflow and volume of the detention pond design. By this method, routing for detention ponds is calculated based on a storage-discharge relationship (Equation below):

$$Q_i(t) - Q_o(t) = \frac{dS}{dt}$$

Equation: Detention Storage Routing (lumped form of continuity equation)

where $Q_i$ is the runoff rate into the detention basin, $Q_o$ is the discharge rate out of the basin, and $dS/dt$ is the change in the storage volume within the basin with respect to time, $t$. In most cases, the stored water is discharged from the basin is through a weir or culvert and the discharge volume is calculated according to outlet dimensions and the weir or orifice equations, respectively. According to HCFCD site runoff curves, pre-development runoff is 1.5-2 CFS/ acre.

| Minimum Detention Volumes and Estimation Method for the 1% (Atlas 14) Storm Event | | | |
|---|---|---|---|
| Project Drainage Area | | Method | Volume (acre-ft/acre) |
| Small | Less than 20 acres | Atlas 14 Site Runoff Curves | ≥ 0.65 |
| Moderate | Between 20 and 640 acres | Small Watershed Method | |
| Large | 640 acres or larger | Detailed hydrologic and hydraulic analysis via Watershed Modeling Method | ≥ 0.55 |

Table E-2. Interim (2019) On-Site Detention Requirements for Harris County (HCFCD)

To understand how current detention storage provided by coastal prairie compared to HCFCD pre-development standards, hydrographs and runoff rates were analyzed both along the channel and corresponding to overland catchments from the *Vflo®®* model. In assessing the hydrographs at watch points corresponding to moderate -scale overland catchments under three different land use scenarios (n=0.1, urbanized; NLCD current conditions; n=0.6, tallgrass prairie), it was confirmed that vegetative roughness imparts a slowing effect mimicking that of an engineered detention pond during rainfall events (Figure 5) . Through this relationship, the detention storage capacity of prairie vegetation can be quantified numerically as the difference between the urbanized hydrograph and the hydrograph of the current conditions or restoration scenario.

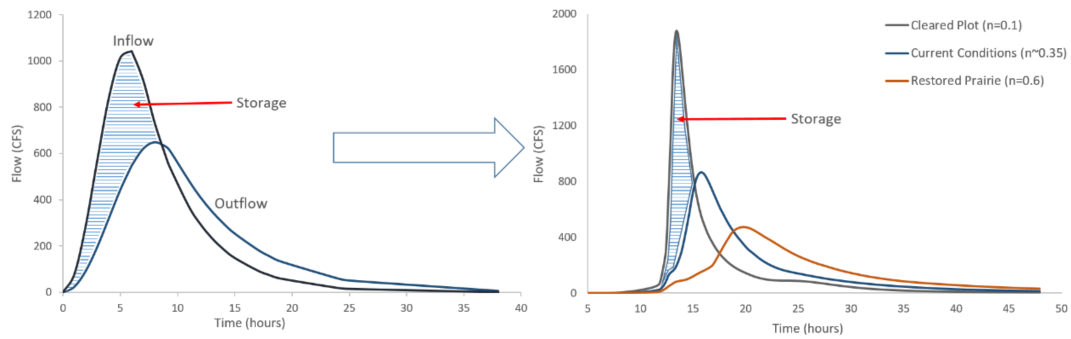



Figure E- 5.Example of Detention Pond routing (left) Modeled Results (right) from 550 acre Plot

The area between the hydrograph was calculated via the trapezoidal method resulting in an estimated storage volume. The volume was assessed at five points along main Cypress Creek and 6 overland catchments within the region of n-value change to both summarize the detention capacity and analyze corresponding spatial variability. The overland catchments varied in size from 280 acres to 915 acres with average slopes between 0.5 -3 %. The average detention capacity in acre-ft/acre created by the influence of overland roughness is summarized in Table 3for both current conditions and restoration conditions compared to the modeled urbanized scenario.

| | *Current Undeveloped Conditions* | | *Prairie Restoration/Expansion* | |
|---|---|---|---|---|
| ***Storm Size*** | *Localized Overland Catchment* | *Channel Catchment* | *Localized Overland Catchment* | *Channel Catchment* |
| *10-yr Atlas 14* | 0.16 | 0.06 | 0.24 | 0.12 |

| | | | | |
|---|---|---|---|---|
| *100-yr Atlas 14* | 0.37 | 0.12 | 0.58 | 0.25 |

Table E- 3.Average Detention Storage (acre-ft/acre)

The average storage volume was considered adequate in capturing the general storage capacity because there was little variability in calculated storage volume between points at both overland and channel catchments (standard deviation less than 0.057 acre-ft/acre for 10-yr and 100-yr storm sizes). However, a significant difference in storage capacity is seen at the channel watch points compared to overland catchments which suggests the channel base flow regimes mute the influence of overland roughness on rainfall-runoff when it reaches the channel. When considering the influence of storm size, the detention storage capacity increases with the volume of rainfall, which was an inconsistent finding compared to the general reduction in peak flow (channel) discussed in the previous section.

To compare the modeled storage to HCFCD detention requirements, hydrographs were generated using the HCFCD site-runoff curves and the Small Watershed Method (for catchments smaller than 640 acres). Explanation of the methodology of the Small Watershed Model can be found in Appendix E along with an example of how it was applied for this study (HCFCD 2019). Using this method, hydrographs were generated for HCFCD's developed condition (85% impervious cover) and HCFCD's "pre-development" condition (0% impervious) for the 100-yr storm and were compared to modeled hydrographs for equivalent sized catchments.

The trapezoidal method was again applied to calculate the volume between the modeled hydrographs and those generated by HCFCD's evaluation methodology. By this comparison, it was concluded that HCFCD's site-runoff curves assume a well-drained, undeveloped scenario which may negate the effects of vegetative roughness. Additional detention storage would need to be provided beyond the HCFCD minimum of 0.65 acre-ft/acre if developing a prairie landscape (Figure 6) ). This is an indication that if developing a coastal prairie landscape, specifically the KPC land, according to Harris County 2019 developmental regulations, rainfall-runoff will be exacerbated in the watershed and surrounding area.

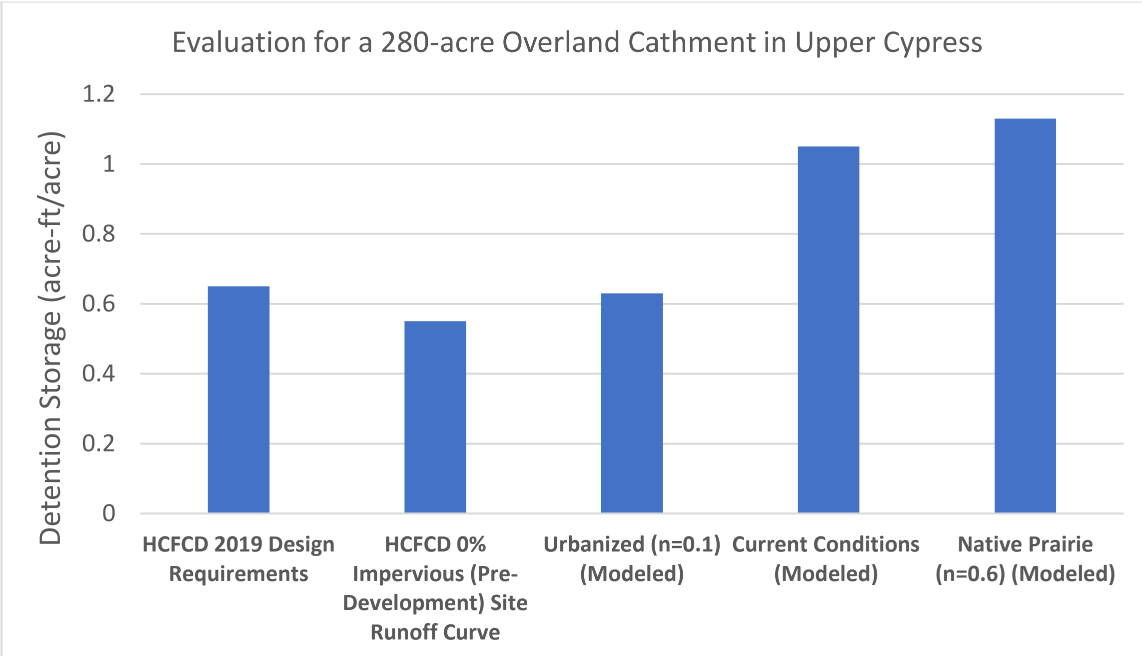



Figure E-6. On-Site Detention Storage when Compared to HCFCD 85% Impervious Scenario

In altering the Manning's roughness coefficient, this study aimed at determining the *relative* impact of overland vegetation on above-ground detention-like effects. However, without considering infiltration, a large retention effect of prairie vegetation is not acknowledged. As discussed in the literature review of this thesis and subsequently verified by a recent field infiltration study conducted by the SSPEED Center on KPC land, prairie vegetation can increase water-retention capacity of topsoil. A prairie expansion would therefore theoretically increase the reduction in peak flow demonstrated by the expansion scenario in this study. Information regarding an infiltration estimate relating to the current conditions of the undeveloped can be found in Appendix C.

## Hydrologic Model Validation and Calibration

**The model was calibrated to discharge data from USGS gages at four locations in Cypress Creek watershed: Katy-Hockley road (1), the intersection of House and Hahl road (2), Grant Road (3) and Little Cypress Creek at Rosehill (4) (Figure ).**

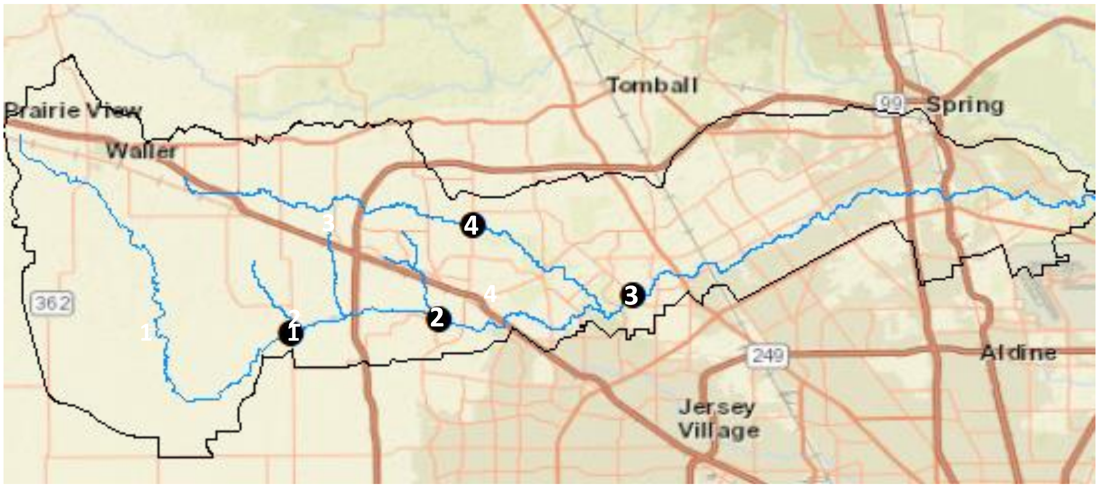



Figure E-7. USGS Gages used for *Vflo®* Model Calibration

**With adjustments to the soil depth, hydraulic conductivity, and roughness, the model was calibrated to an above satisfactory level for both Harvey and the Tax Day storms based on NSE (**Table E-**),** $R^2$ **and percent difference performance metrics.**

| Storm | Metric | Gage Location | | | |
|---|---|---|---|---|---|
| | | Katy-Hockley (1) | House & Hahl (2) | Little Cypress (3) | Grant Road (4) |
| April 2016 (Tax Day) | $R^2$ | Gage Break | 0.63 | 0.95 | 0.95 |
| | NSE | Gage Break | 0.84 | 0.97 | 0.97 |
| Harvey | $R^2$ | 0.94 | 0.88 | 0.91 | 0.94* |
| | NSE | 0.92 | 0.86 | 0.80 | 0.92* |

Table E-4 Model NSE and $R^2$ Results after Calibration

**Quantity and quality of the observed data from USGS was the biggest issue in calibrating to these storms. During the Tax Day storm, the gage broke at Katy-Hockley, and during Harvey a significant portion of the storm went unrecorded at Grant Road. Additionally, previous studies conducted in this watershed by Rice University's SSPEED Center highlighted issues with the accuracy and consistency of the data at the House-Hahl gage, and for this reason model performance comparison at this gage was not heavily weighted. Discrepancy in the calibration at this gage for the Tax Day storm ($R^2$ = 0.63) is, however, thought to partially attributed to building the model with new terrain data (2018 Lidar) which shows modifications in the terrain near House-Hahl occurring post April 2016. This is elaborated on in section** Error! Reference source not found.**; but, the changes in terrain potentially resulted in altering the model flow network to be unrepresentative of the time-period of the storm, hence altering model response at the House-Hahl gage (Figure ).**

**The results after calibration for both Hurricane Harvey and Tax Day can be seen below.**

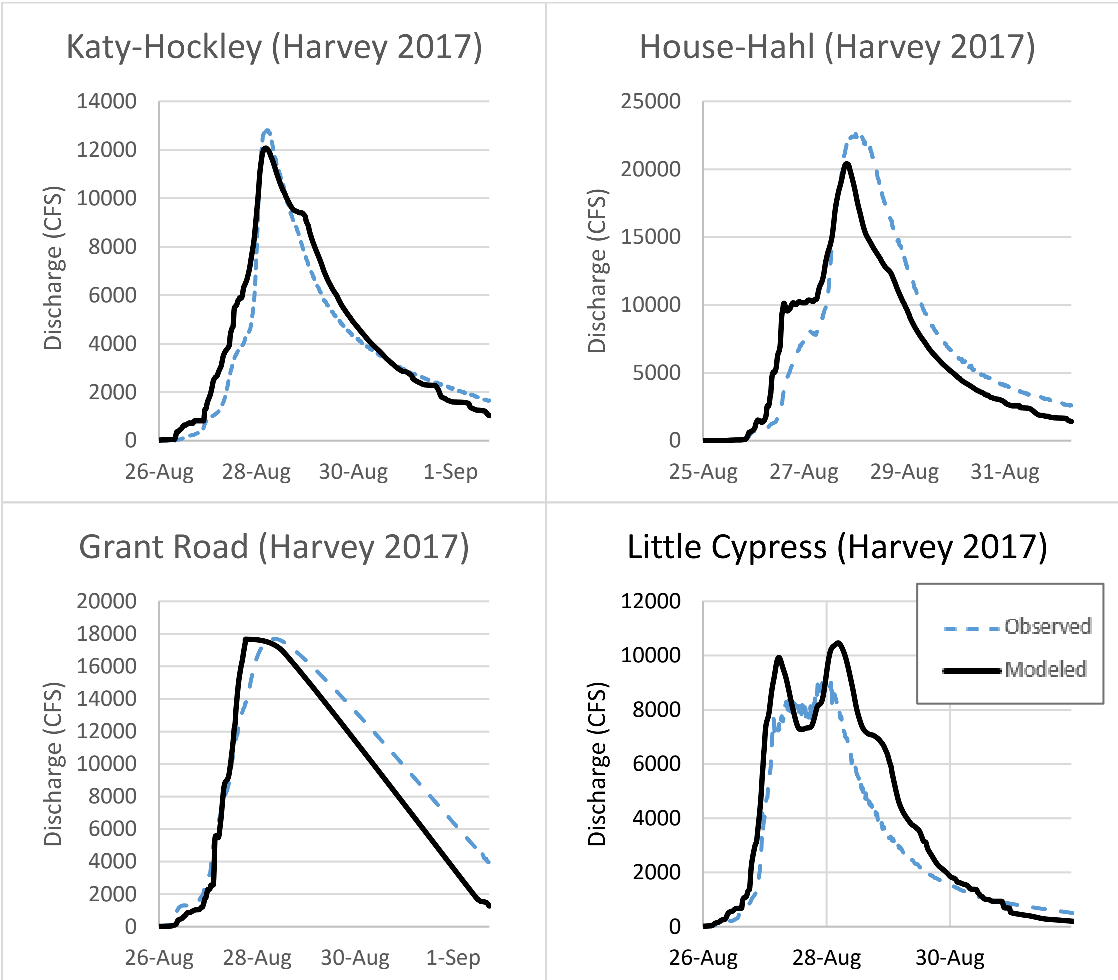



**Figure E-8 Hydrograph results after Calibration – Hurricane Harvey**

**Modeled (black) and USGS Gage Data (dashed)**

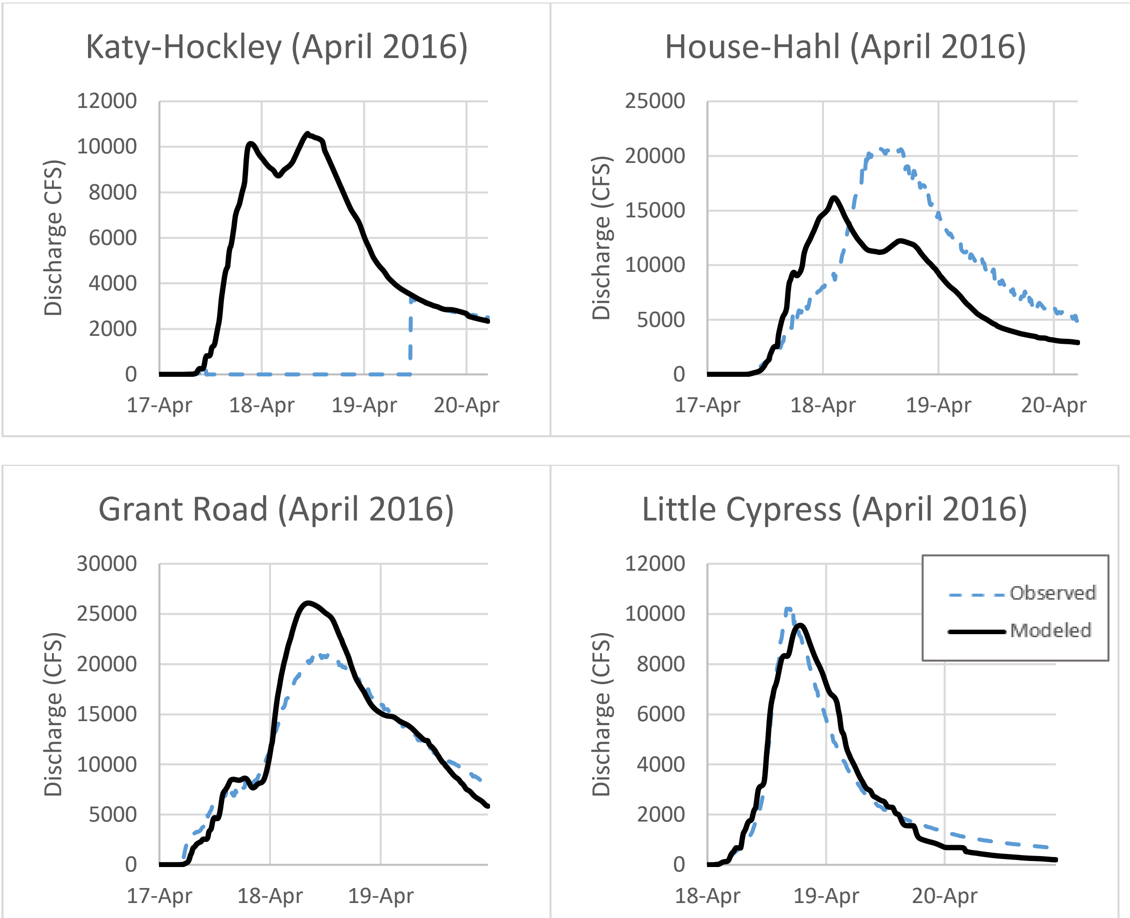



**Figure E-9 Hydrograph Results after Calibration - Tax Day**

## Appendix F. Hydrologic/Hydraulic Modeling Using HEC-RAS 2D

An analysis was performed using a rain-on-grid HEC-RAS 2D model, covering portions of upper Cypress Creek and Addicks watersheds, to estimate the detention benefits of converting current land cover to native prairie vegetation for the existing 20,000 acres of CPC lands (green shaded area), as well as an additional 10,000 acres of land in the vicinity of the CPC lands, for a total of 30,000 acres (brown shaded area), as shown in **Figure F-1.**

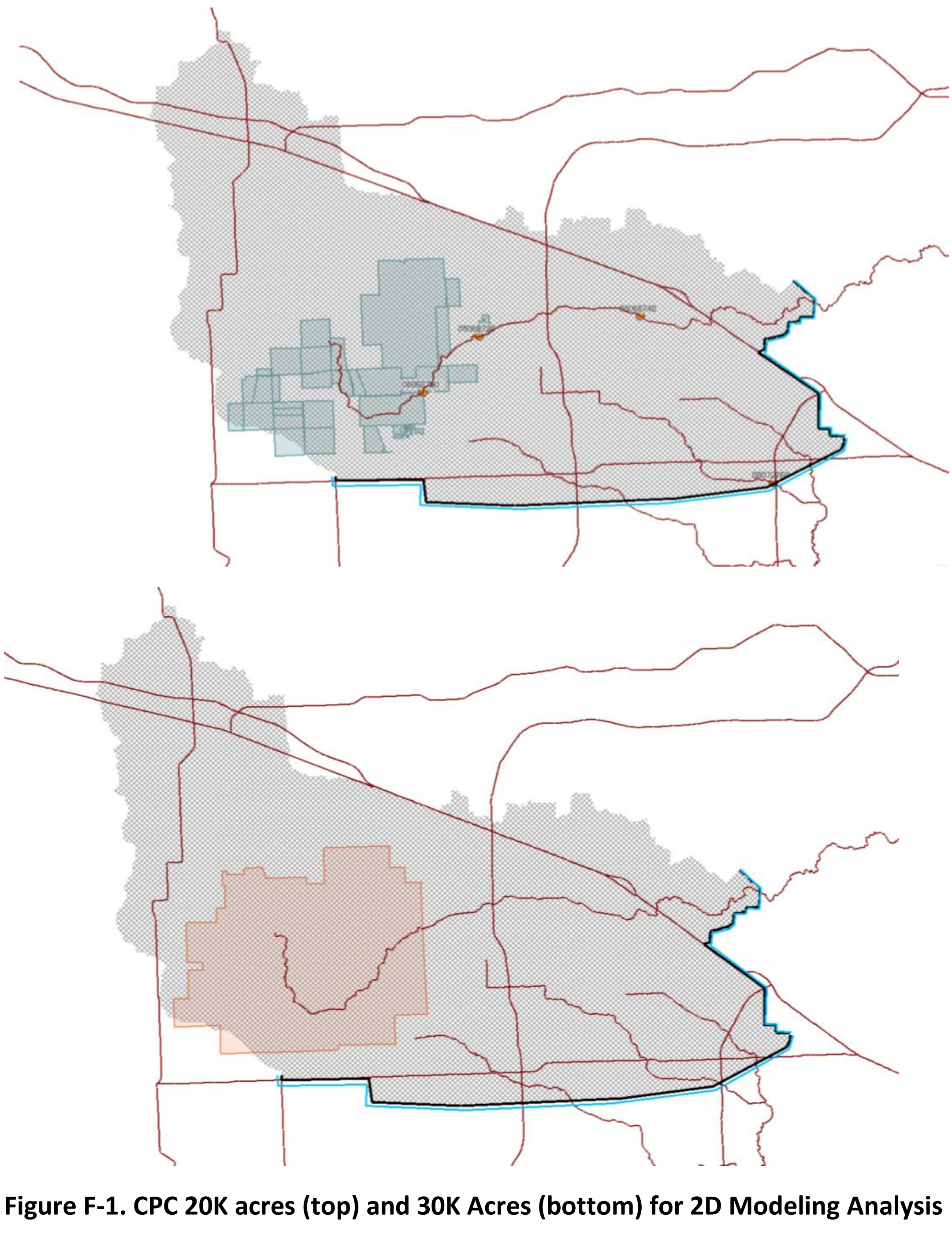


**Figure F-1. CPC 20K acres (top) and 30K Acres (bottom) for 2D Modeling Analysis**

The HEC-RAS 2D modeling for this analysis incorporated the following:

- HEC-RAS 2D (Version 6.4.1)
- Domain: Upper Cypress Creek watershed + Cypress / Addicks overflow area
- Cell resolution: 300 ft x 300 ft
- Breaklines placed along main channels and major roadways / highways
- Boundary conditions: Normal Depth
- Inflow: rain-on-grid
    - HCFCD 15-min gage rainfall – Thiessen Polygon (Harvey '17 and Tax Day '16)
    - NOAA Atlas 14 2018 hyetograph (design storms)

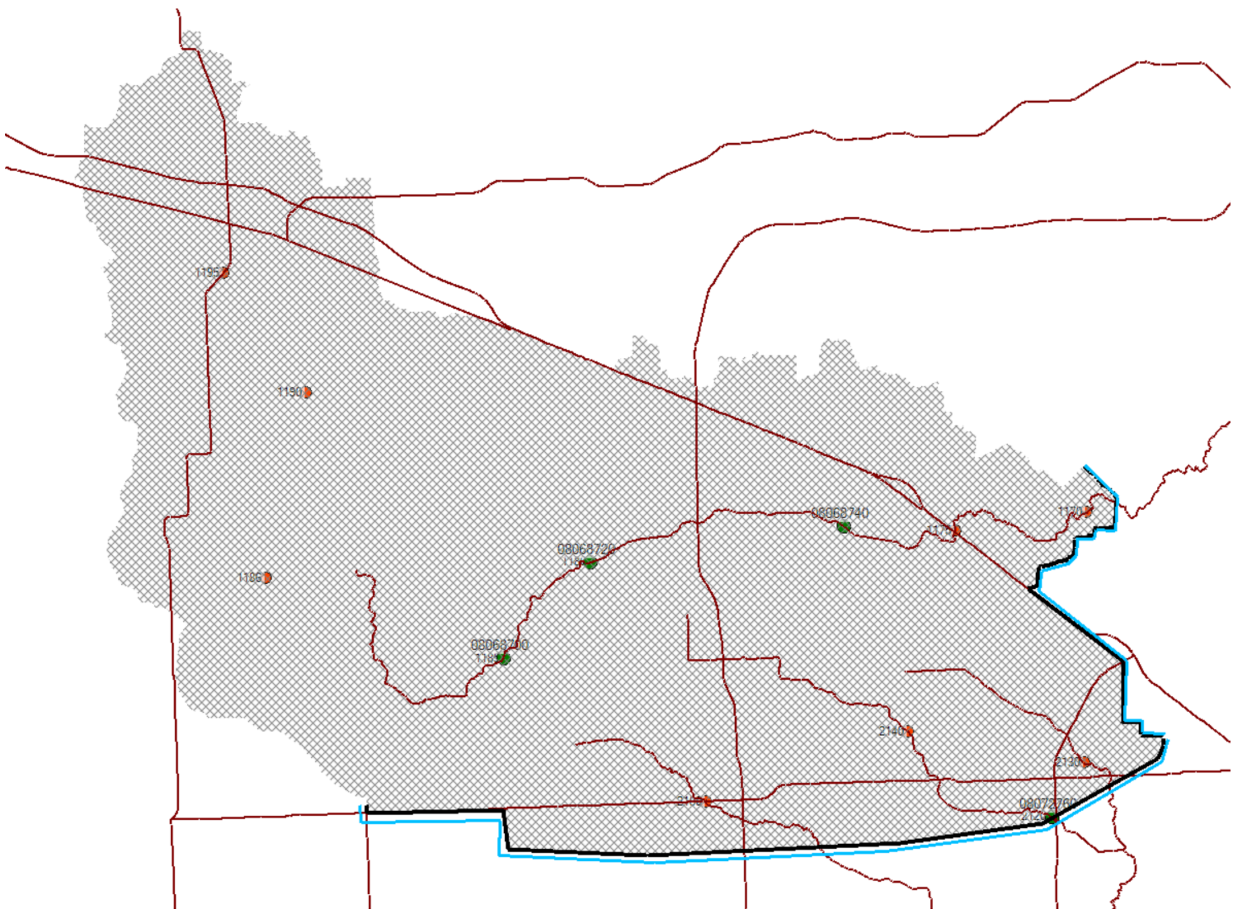



**Figure F-2. HEC-RAS 2D Model for Portions of Upper Cypress Creek and Addicks Watersheds**

Other spatial data inputs to the 2D model include terrain (topo), soil type (with infiltration parameters), land use/land cover (with Manning's roughness values), and rainfall as reflected in the following figures:

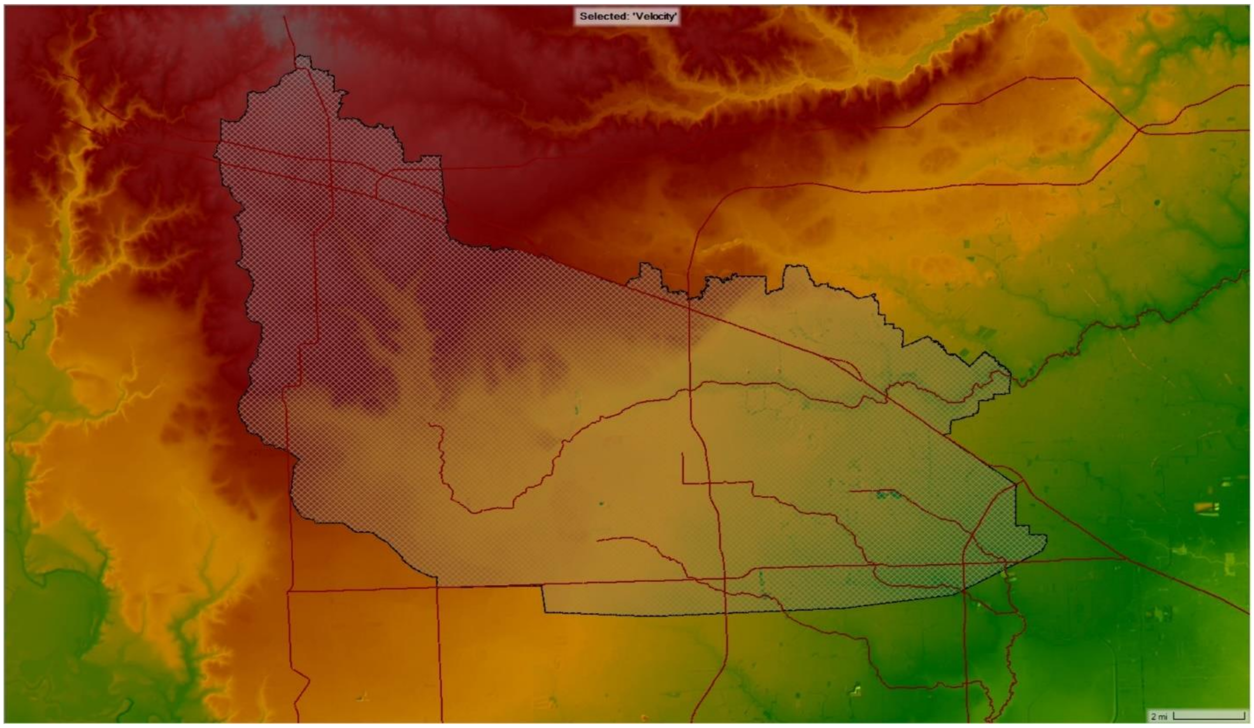



**Figure F-3. Terrain Based on USGS DEM (10m) for Spatial Input**

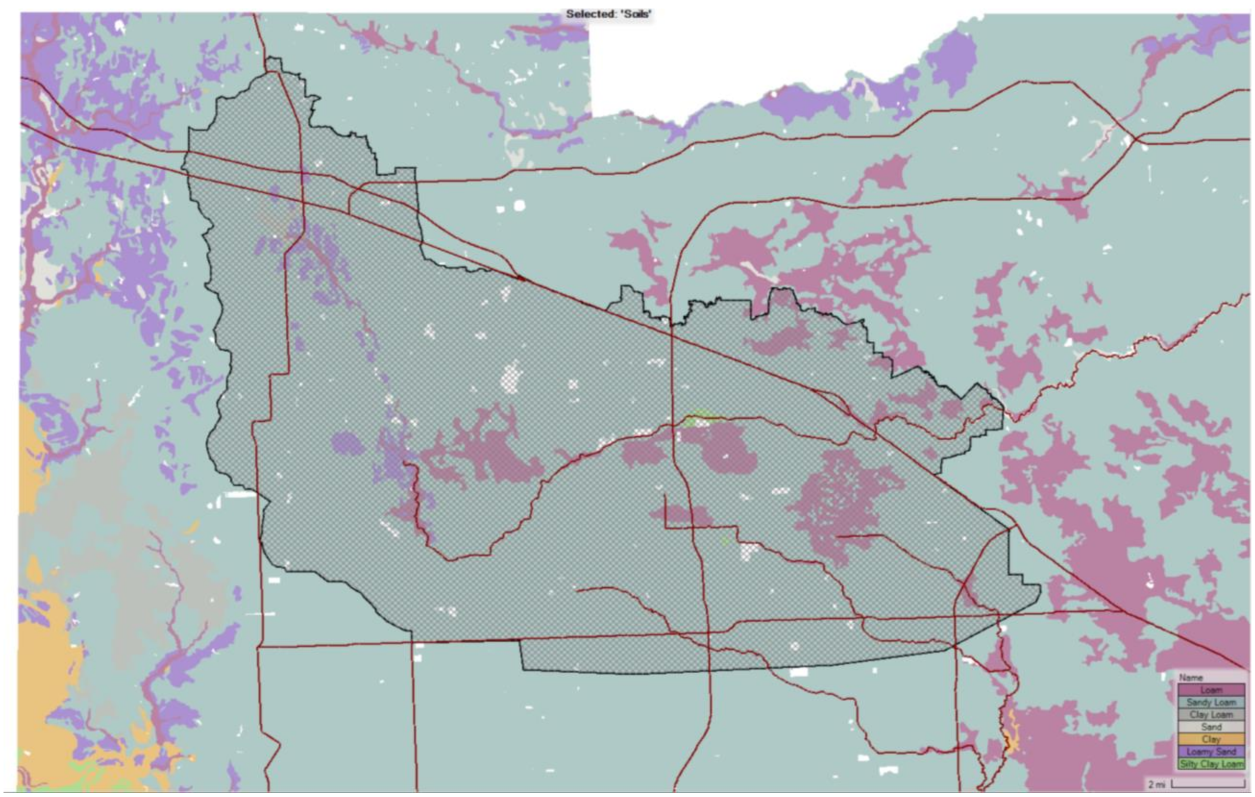



**Figure F-4. Soils Type from NRCS (2018) for Spatial Input**

| ID | Name | Wetting Front Suction (in) | Saturated Hydraulic Conductivity (in/hr) | Initial Soil Water Content | Saturated Soil Water Content | Residual Soil Water Content | Pore Size Distribution Index |
|---|---|---|---|---|---|---|---|
| 0 | NoData | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | Loam | 3.5 | 0.1 | 0.463 | 0.463 | 0.027 | 0.252 |
| 2 | Sandy Loam | 4.3 | 0.2 | 0.453 | 0.453 | 0.041 | 0.378 |
| 3 | Clay Loam | 8.2 | 0.04 | 0.464 | 0.464 | 0.075 | 0.242 |
| 4 | Sand | 1.9 | 4.6 | 0.437 | 0.437 | 0.02 | 0.694 |
| 5 | Clay | 12.5 | 0.01 | 0.475 | 0.475 | 0.09 | 0.165 |
| 6 | Loamy Sand | 2.4 | 1.2 | 0.437 | 0.437 | 0.035 | 0.553 |
| 7 | Silty Clay Loam | 8.6 | 0.04 | 0.471 | 0.471 | 0.04 | 0.177 |

Note:

- Green and Ampt infiltration parameter values are adapted from HEC-HMS and HEC-RAS 2D User Manual based on Rawls, Brakensiek, and Miller (1983)
- Initial soil water content is set equal to saturated water content to represent fully saturated antecedent soil moisture condition
- Modeled infiltration is currently only based on soil type (i.e., does not account for land cover or vegetation type)

**Figure F-5. Model Input Parameters for Infiltration Based On Soil Type**

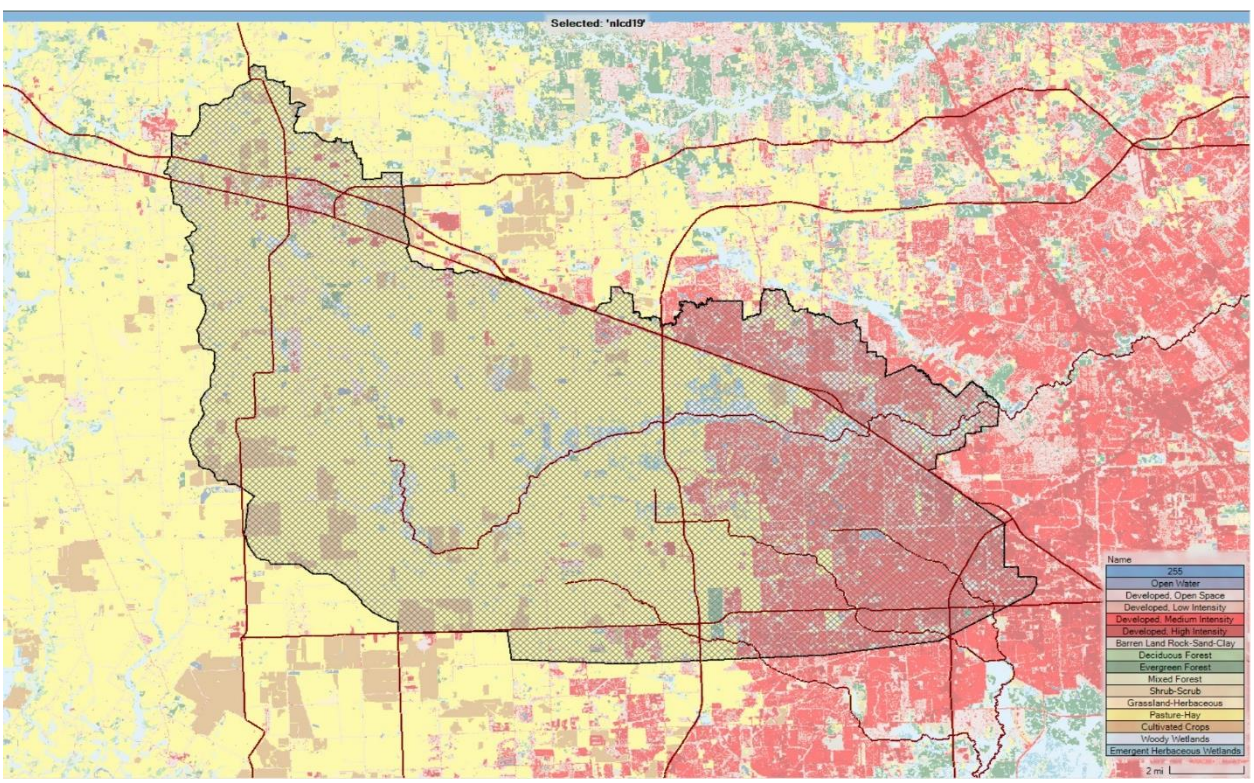



**Figure F-6. Land Cover from NLCD (2019) for Spatial Input**

**Baseline**
Existing CPC owned land (2023)

| ID | Name | ManningsN | Percent Impervious |
|---|---|---|---|
| 0 | NoData | | 100 |
| 1 | 255 | | 100 |
| 2 | CPC | 0.35 | 0 |
| 11 | Open Water | 0.015 | 100 |
| 21 | Developed, Open Space | 0.0404 | 100 |
| 22 | Developed, Low Intensity | 0.0678 | 50 |
| 23 | Developed, Medium Intensity | 0.0678 | 80 |
| 24 | Developed, High Intensity | 0.0404 | 100 |
| 31 | Barren Land Rock-Sand-Clay | 0.113 | 30 |
| 41 | Deciduous Forest | 0.36 | 0 |
| 42 | Evergreen Forest | 0.32 | 0 |
| 43 | Mixed Forest | 0.4 | 0 |
| 52 | Shrub-Scrub | 0.4 | 0 |
| 71 | Grassland-Herbaceous | 0.368 | 0 |
| 81 | Pasture-Hay | 0.325 | 0 |
| 82 | Cultivated Crops | 0.325 | 30 |
| 90 | Woody Wetlands | 0.086 | 0 |
| 95 | Emergent Herbaceous Wetlan... | 0.1825 | 30 |

**Scenario 1**
Planned CPC land (30,000 ac)

| ID | Name | ManningsN | Percent Impervious |
|---|---|---|---|
| 0 | NoData | | 100 |
| 1 | 255 | | 100 |
| 2 | CPC2 | 0.6 | 0 |
| 11 | Open Water | 0.015 | 100 |
| 21 | Developed, Open Space | 0.0404 | 100 |
| 22 | Developed, Low Intensity | 0.0678 | 50 |
| 23 | Developed, Medium Intensity | 0.0678 | 80 |
| 24 | Developed, High Intensity | 0.0404 | 100 |
| 31 | Barren Land Rock-Sand-Clay | 0.113 | 30 |
| 41 | Deciduous Forest | 0.36 | 0 |
| 42 | Evergreen Forest | 0.32 | 0 |
| 43 | Mixed Forest | 0.4 | 0 |
| 52 | Shrub-Scrub | 0.4 | 0 |
| 71 | Grassland-Herbaceous | 0.368 | 0 |
| 81 | Pasture-Hay | 0.325 | 0 |
| 82 | Cultivated Crops | 0.325 | 30 |
| 90 | Woody Wetlands | 0.086 | 0 |
| 95 | Emergent Herbaceous Wetlan... | 0.1825 | 30 |

**Note**:

- Roughness values for NLCD classes are referenced from Kalyanapu et al. 2009
- Roughness value for 20K acres of CPC land in Baseline set to 0.35 (to match existing conditions) and for 30K acres Scenario 1 set to 0.6 (ref. Weltz et al. 1992)
- Channel roughness is set to 0.035 for Cypress Cr., and 0.045 for Bear, Langham, and Horsepen Cr.

**Figure F-7. Tabulation of Roughness Values for Each Land Cover Type**

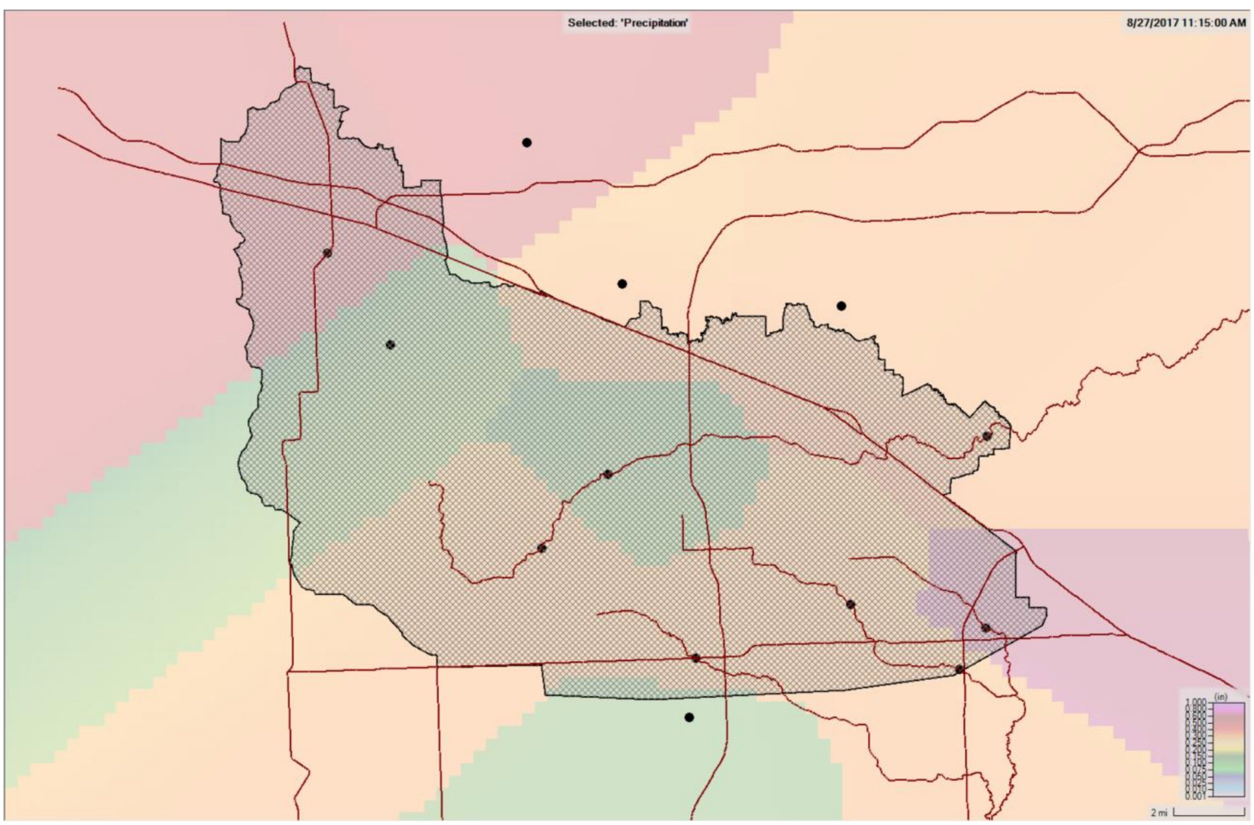



**Figure F-8. Locations of HCFCD Rain Gages used for Historic Storm Simulations**

NOAA Atlas 14, Volume 11, Version 2
Location name: Hockley, Texas, USA*
Latitude: 29.9679°, Longitude: -95.8206°
Elevation: 170 ft**
* source: ESRI Maps
** source: USGS

**POINT PRECIPITATION FREQUENCY ESTIMATES**

Sanja Perica, Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Orlan Wilhite

NOAA, National Weather Service, Silver Spring, Maryland

PF_tabular | PF_graphical | Maps_&_aerials

**PF tabular**

| PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Duration | Average recurrence interval (years) | | | | | | | | | |
| | 1 | 2 | 5 | 10 | 25 | 50 | 100 | 200 | 500 | 1000 |
| 5-min | 0.487 (0.369-0.644) | 0.567 (0.433-0.742) | 0.697 (0.531-0.916) | 0.805 (0.604-1.07) | 0.952 (0.690-1.30) | 1.06 (0.751-1.50) | 1.18 (0.811-1.70) | 1.30 (0.873-1.93) | 1.47 (0.953-2.26) | 1.60 (1.01-2.53) |
| 10-min | 0.772 (0.585-1.02) | 0.900 (0.688-1.18) | 1.11 (0.845-1.46) | 1.28 (0.962-1.71) | 1.52 (1.10-2.09) | 1.70 (1.20-2.40) | 1.88 (1.30-2.73) | 2.07 (1.39-3.07) | 2.31 (1.50-3.55) | 2.49 (1.58-3.93) |
| 15-min | 0.983 (0.744-1.30) | 1.14 (0.871-1.49) | 1.40 (1.06-1.84) | 1.61 (1.21-2.14) | 1.90 (1.38-2.60) | 2.11 (1.49-2.98) | 2.33 (1.61-3.38) | 2.57 (1.73-3.83) | 2.90 (1.88-4.47) | 3.16 (2.00-4.99) |
| 30-min | 1.41 (1.06-1.86) | 1.62 (1.24-2.13) | 1.98 (1.51-2.60) | 2.27 (1.70-3.02) | 2.66 (1.92-3.63) | 2.95 (2.08-4.15) | 3.25 (2.24-4.71) | 3.59 (2.42-5.36) | 4.09 (2.66-6.32) | 4.51 (2.85-7.12) |
| 60-min | 1.84 (1.40-2.43) | 2.14 (1.64-2.81) | 2.64 (2.01-3.46) | 3.04 (2.28-4.05) | 3.60 (2.60-4.91) | 4.01 (2.82-5.63) | 4.45 (3.07-6.45) | 4.97 (3.34-7.41) | 5.76 (3.75-8.90) | 6.43 (4.07-10.2) |
| 2-hr | 2.21 (1.68-2.91) | 2.67 (2.02-3.43) | 3.37 (2.57-4.39) | 3.99 (3.00-5.29) | 4.88 (3.55-6.64) | 5.58 (3.96-7.83) | 6.38 (4.42-9.21) | 7.35 (4.96-10.9) | 8.86 (5.78-13.6) | 10.2 (6.46-16.0) |
| 3-hr | 2.41 (1.84-3.16) | 2.98 (2.25-3.78) | 3.83 (2.92-4.96) | 4.61 (3.48-6.09) | 5.77 (4.21-7.85) | 6.72 (4.78-9.43) | 7.83 (5.43-11.3) | 9.18 (6.20-13.6) | 11.3 (7.38-17.4) | 13.2 (8.38-20.7) |
| 6-hr | 2.76 (2.11-3.60) | 3.54 (2.65-4.39) | 4.65 (3.56-5.98) | 5.72 (4.34-7.53) | 7.36 (5.42-10.0) | 8.77 (6.29-12.3) | 10.4 (7.27-15.0) | 12.4 (8.43-18.3) | 15.6 (10.2-23.8) | 18.3 (11.7-28.6) |
| 12-hr | 3.13 (2.41-4.07) | 4.13 (3.07-5.03) | 5.50 (4.22-7.02) | 6.86 (5.22-8.99) | 8.99 (6.67-12.2) | 10.9 (7.85-15.2) | 13.1 (9.17-18.7) | 15.7 (10.7-23.0) | 19.7 (12.9-30.0) | 23.1 (14.8-36.0) |
| 24-hr | 3.55 (2.74-4.58) | 4.77 (3.54-5.73) | 6.42 (4.94-8.15) | 8.10 (6.19-10.6) | 10.7 (8.03-14.6) | 13.1 (9.56-18.4) | 16.0 (11.2-22.7) | 19.1 (13.0-27.7) | 23.6 (15.6-35.7) | 27.4 (17.6-42.6) |

**Figure F-9. Atlas 14 Rainfall Data for Synthetic Frequency Storm Simulations**

Once the HEC-RAS 2D model was set-up with the various spatial data inputs presented above, the model was run for both the Harvey 2017 and Tax Day 2016 storm events to validate its results against observed USGS data at its stream gages along Cypress Creek at Katy Hockley and House Hahl, as well as the gage along Langham Creek in the Addicks watershed. These model result comparisons of both the flow and stage hydrographs with the USGS reported values are shown below in **Figures 10a-c** for the Harvey storm, and **Figures 11a-c** for the Tax Day storm. The comparisons look good, except for the peak flows at the House Hahl gage where the USGS peak flows are much higher than the modeled values. There is a question as to the accuracy of the rating curve being used by the USGS at this gage to convert its stages to flows. The maximum inundation for each of these two storm events across the model domain is shown in **Figure 12** for the Harvey 2017 event and in **Figure 13** for the Tax Day 2016 event.

With the model validated, it was run for the 100, 50, 25, 10, 5 and 2-year frequency storm events using Atlas 14 rainfall data, with the resulting flow hydrographs shown that overflow from Cypress Creek into the Addicks watershed, along with the flows shown at Katy Hockley and House Hahl gages along Cypress Creek and at the Langham Creek gage, in **Figures 15a-d.**

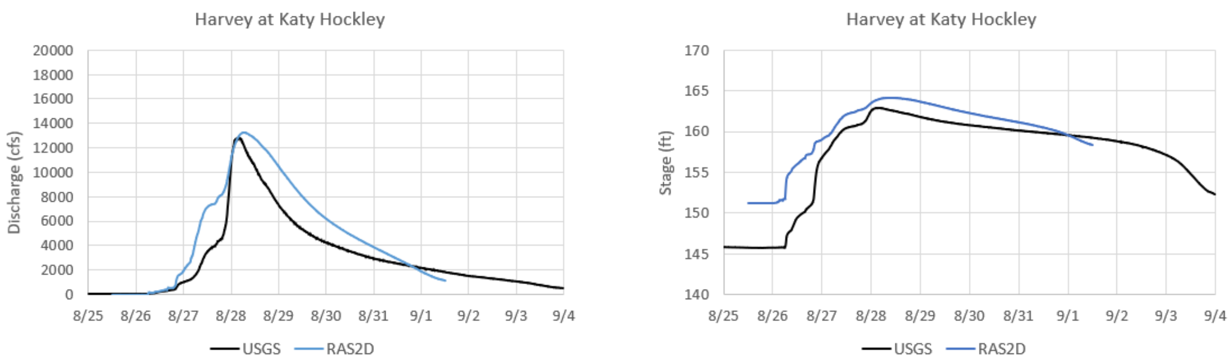



**Figure F-10a. Model Validation for Harvey 2017 at Katy Hockley Gage**

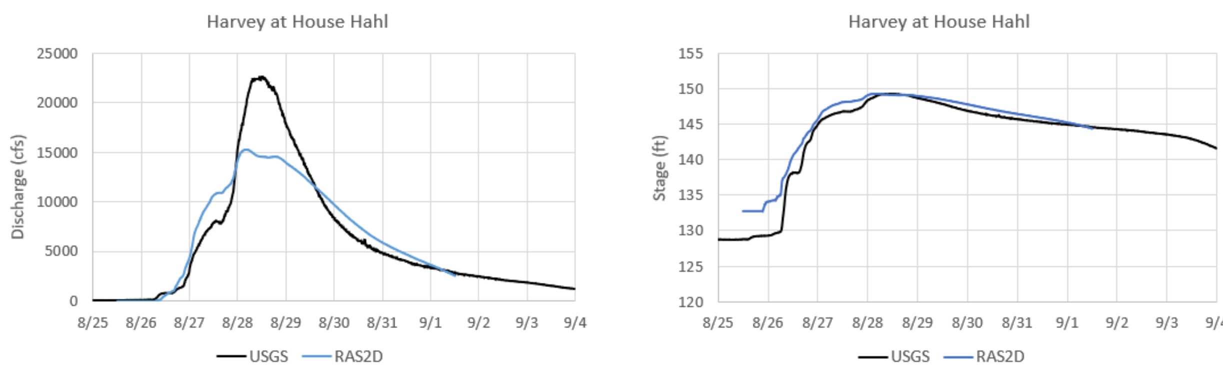



**Figure F-10b. Model Validation for Harvey 2017 at House Hahl Gage**

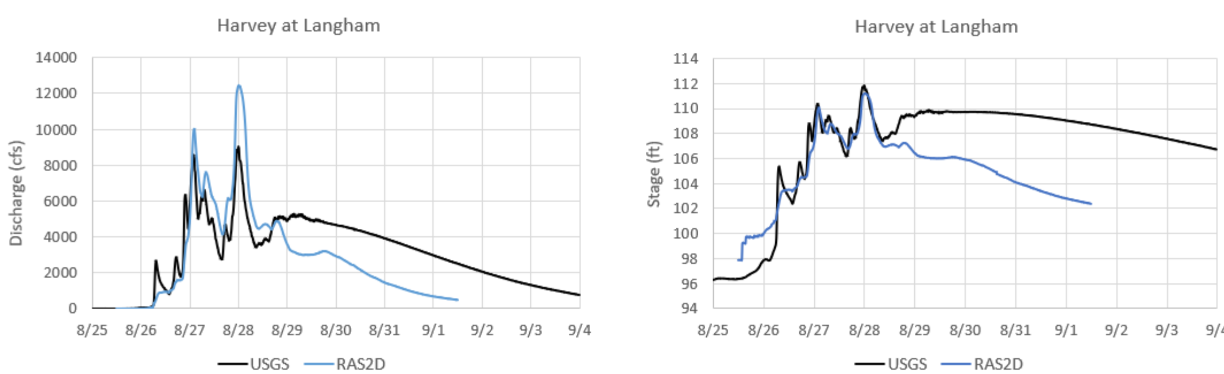



**Figure F-10c. Model Validation for Harvey 2017 at Langham Creek Gage**

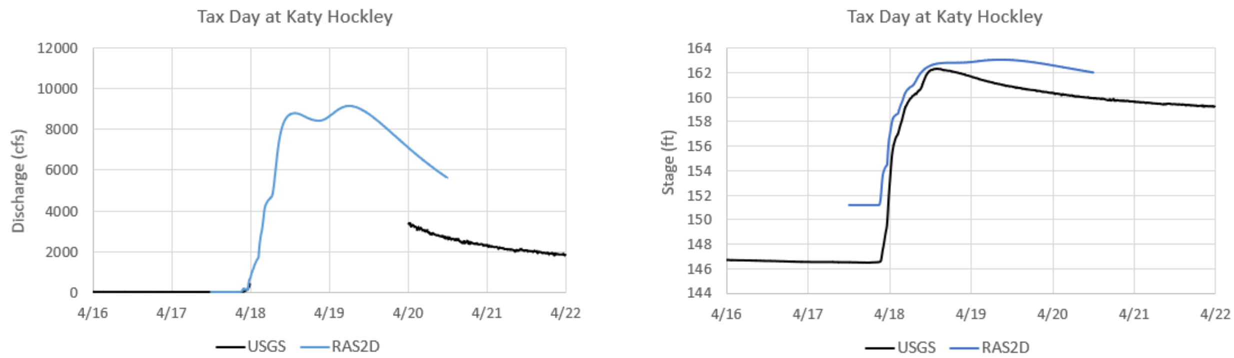



**Figure F-11a. Model Validation for Tax Day 2016 at Katy Hockley Gage**

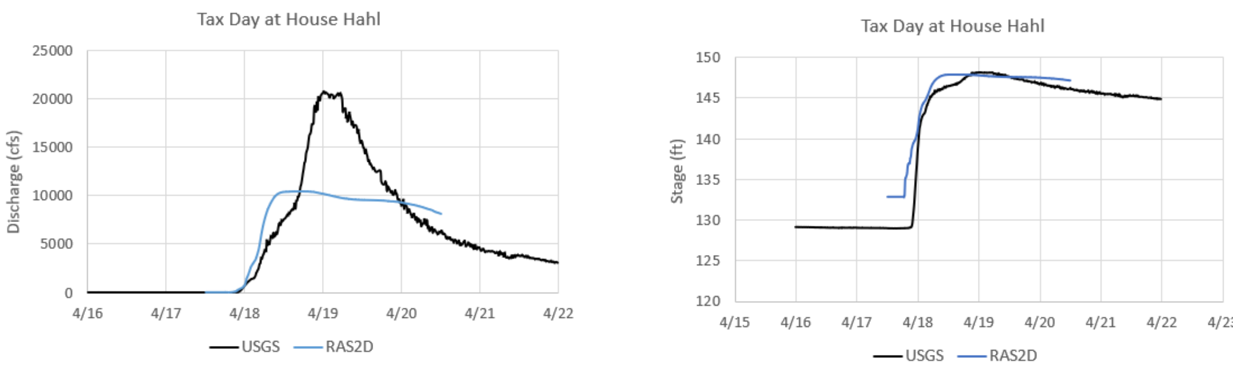



**Figure F-11b. Model Validation for Tax Day 2016 at House Hahl Gage**

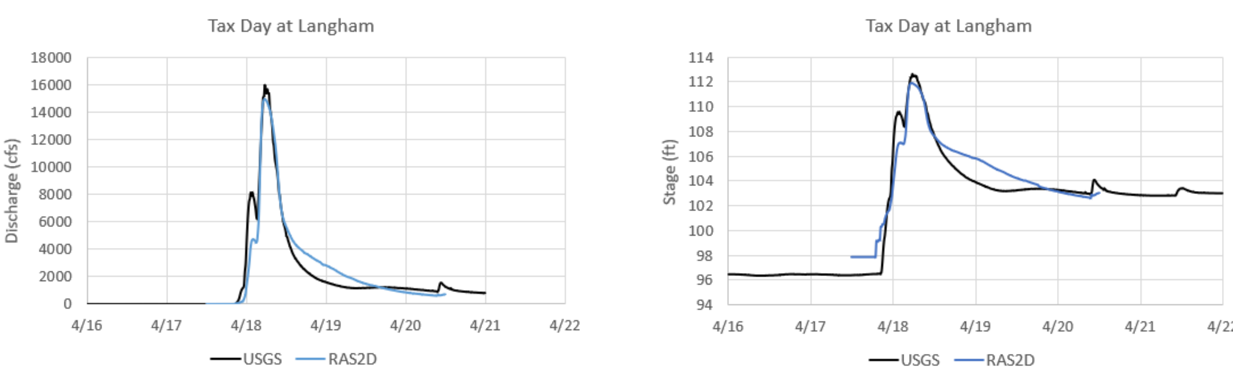



**Figure F-11c. Model Validation for Tax Day 2016 at Langham Creek Gage**

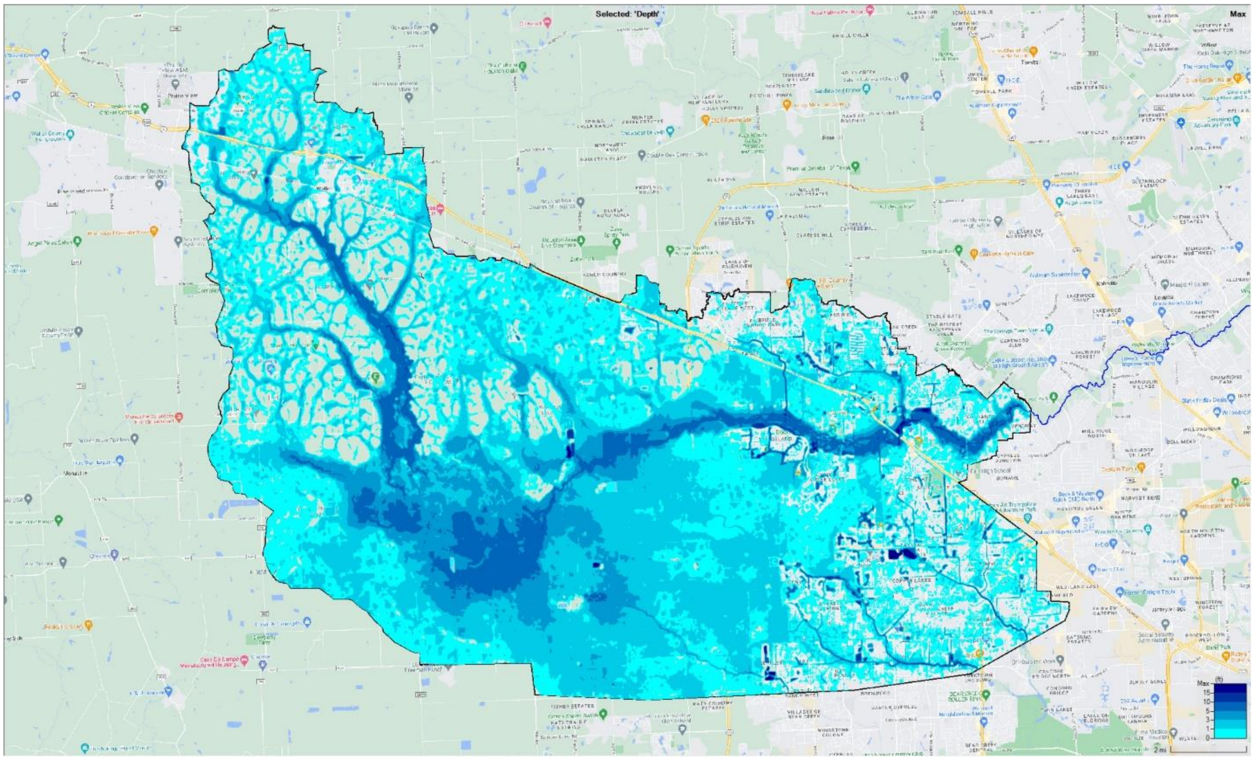



**Figure F-12. Maximum Modeled Inundation for Harvey 2017**

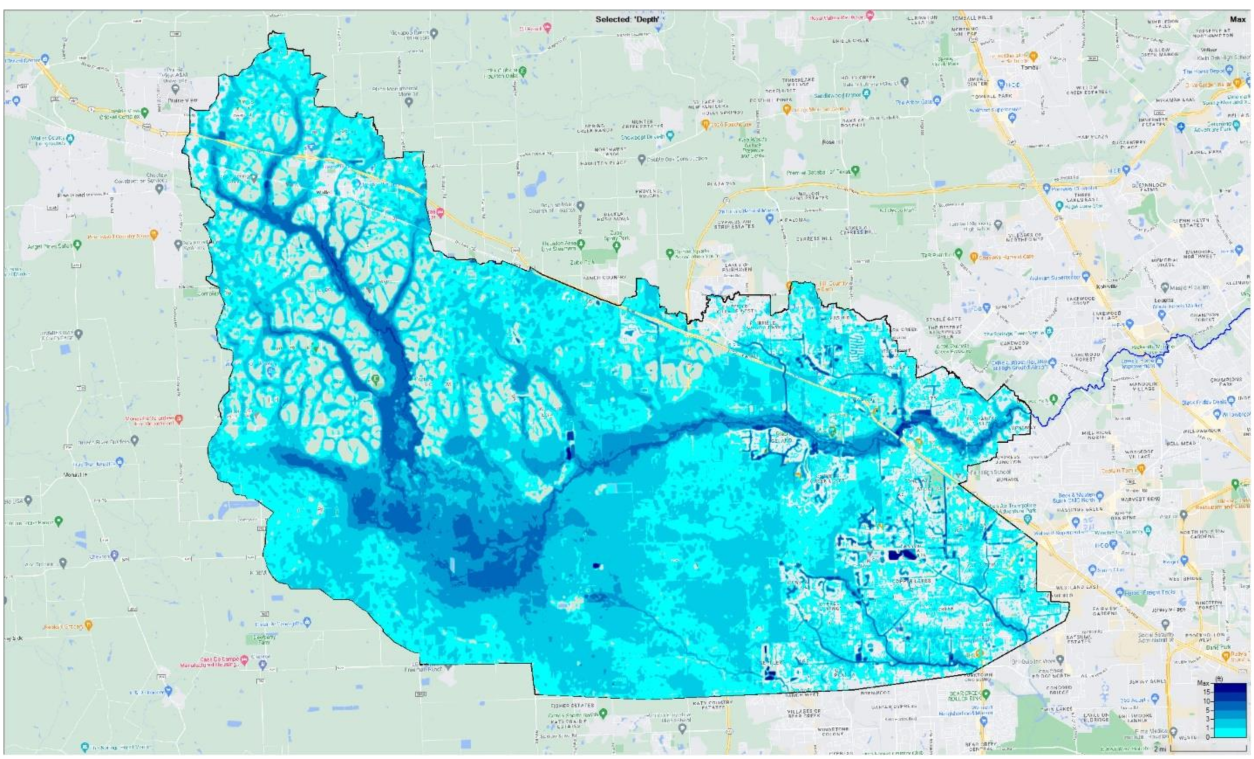



**Figure F-13. Maximum Modeled Inundation for Tax Day 2016**

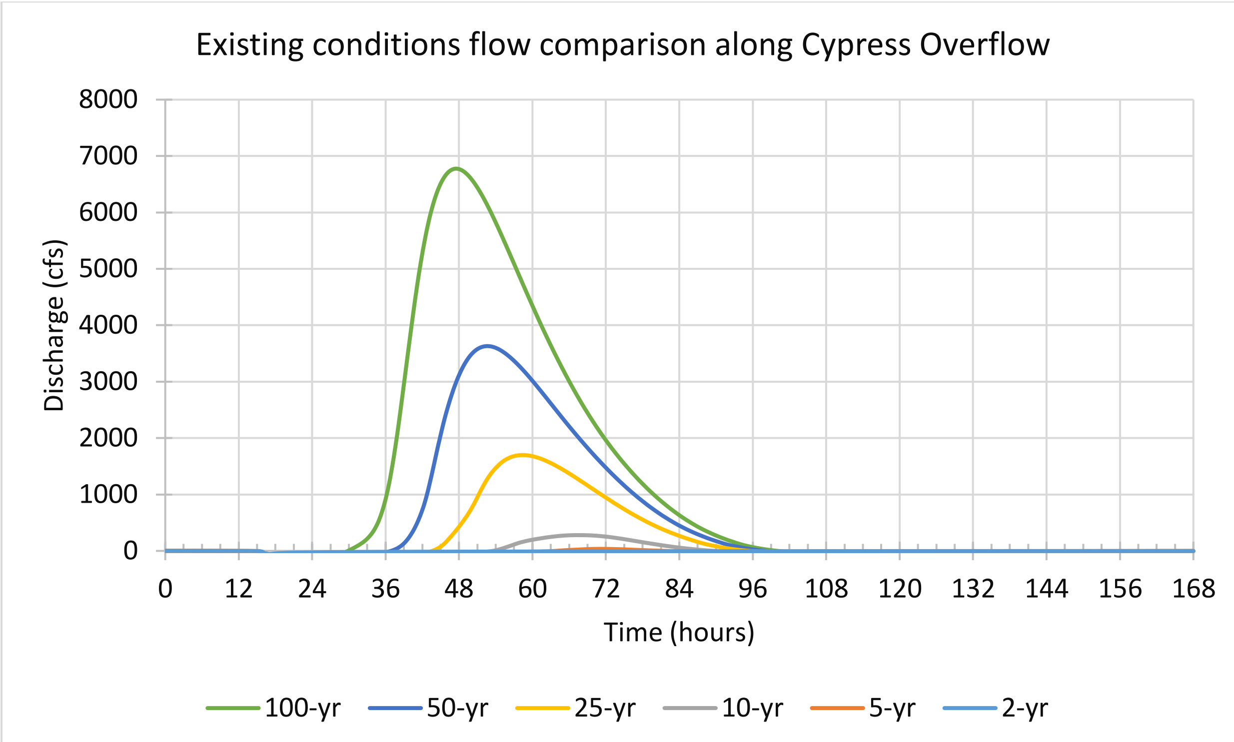



**Figure F-14a. Modeled Existing Flows for Various Frequency Storm Events**

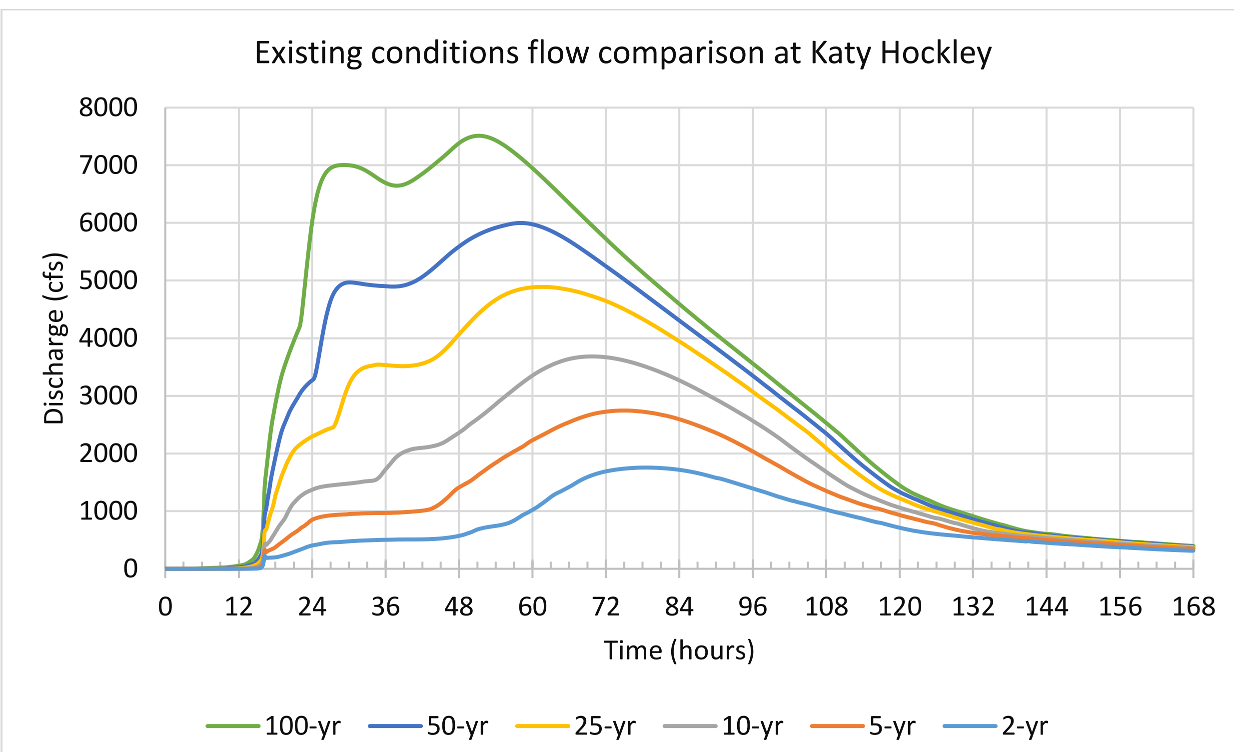



**Figure F-14b. Modeled Existing Flows for Various Frequency Storm Events**

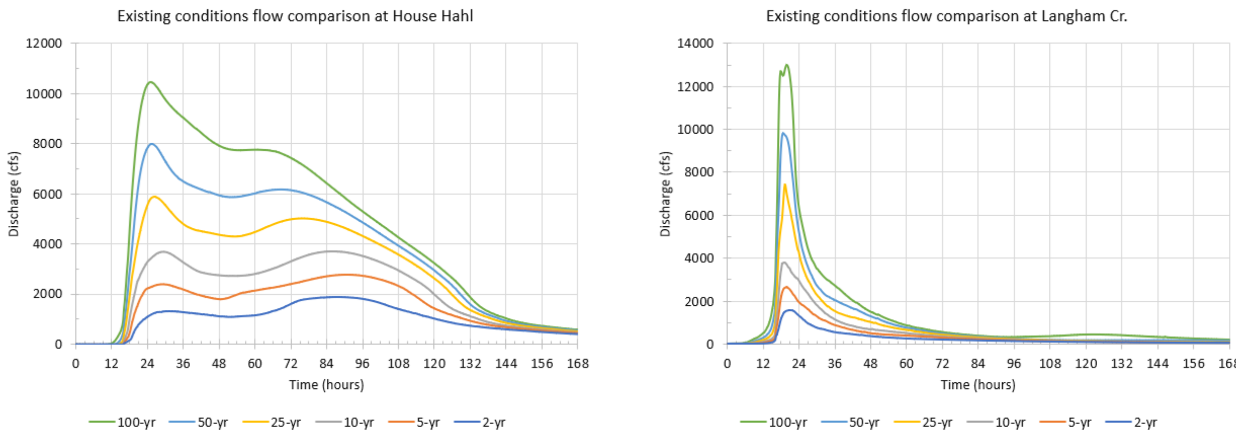



**Figure F-14c. Modeled Existing Flows for Various Frequency Storm Events**

These model results show that Cypress Creek overflows into the Addicks watershed starting with the 5-year storm event. The rest of the runoff continues downstream along Cypress Creek as shown in the results at the Katy Hockley gage, where there is a double peak shown. The earlier peak is the runoff from the local rainfall occurring between the overflow area and this gage. This double peak is also shown at the House Hahl gage.

The maximum modeled inundation for these various frequency storm events is shown in **Figures 15a-f**, starting with the 100-year event and ending with the 2-year event.

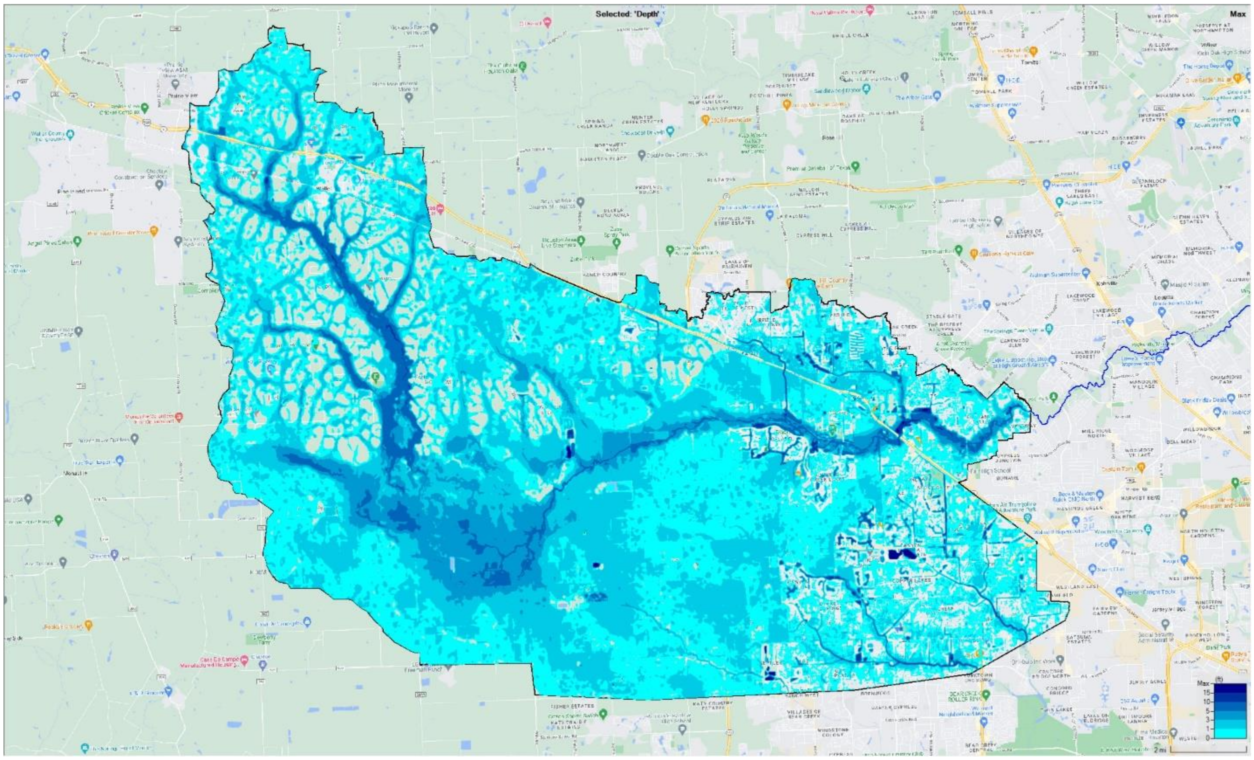


**Figure F-15a. Maximum Modeled Inundation for the 100-year Frequency Storm Event**

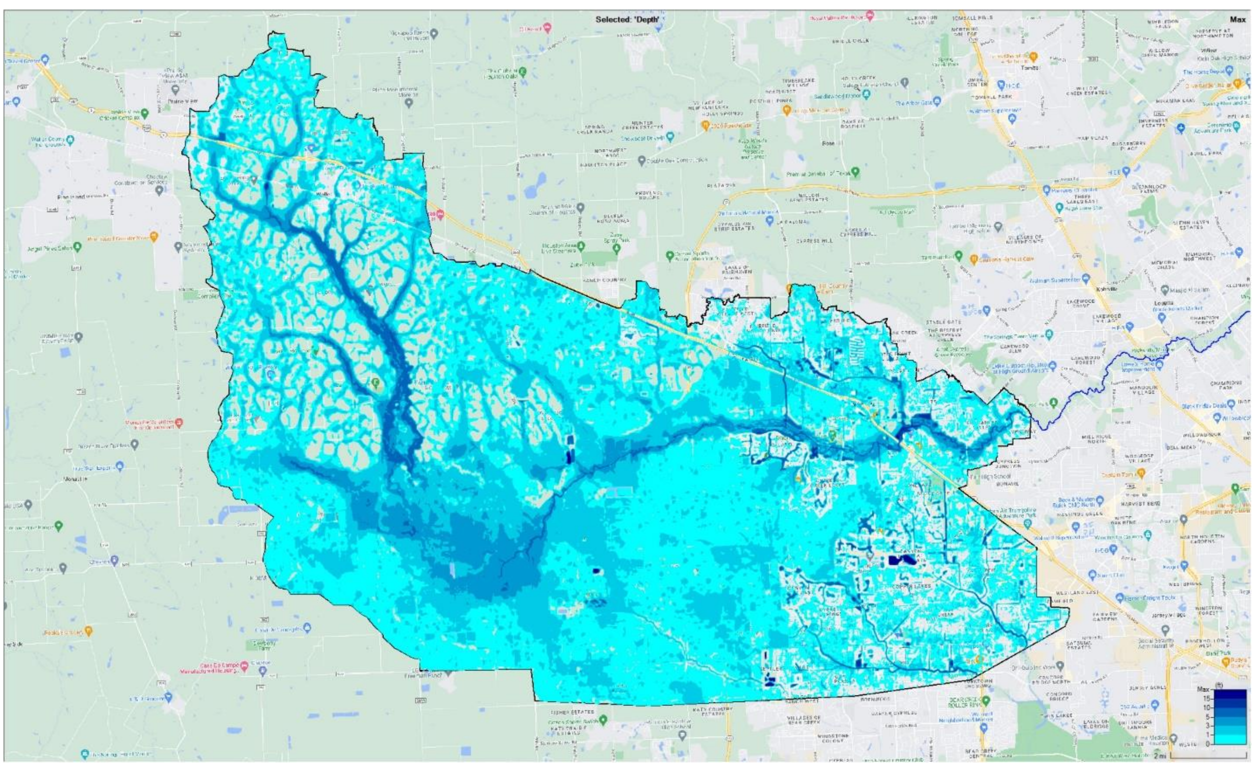


**Figure F-15b. Maximum Modeled Inundation for the 50-year Frequency Storm Event**

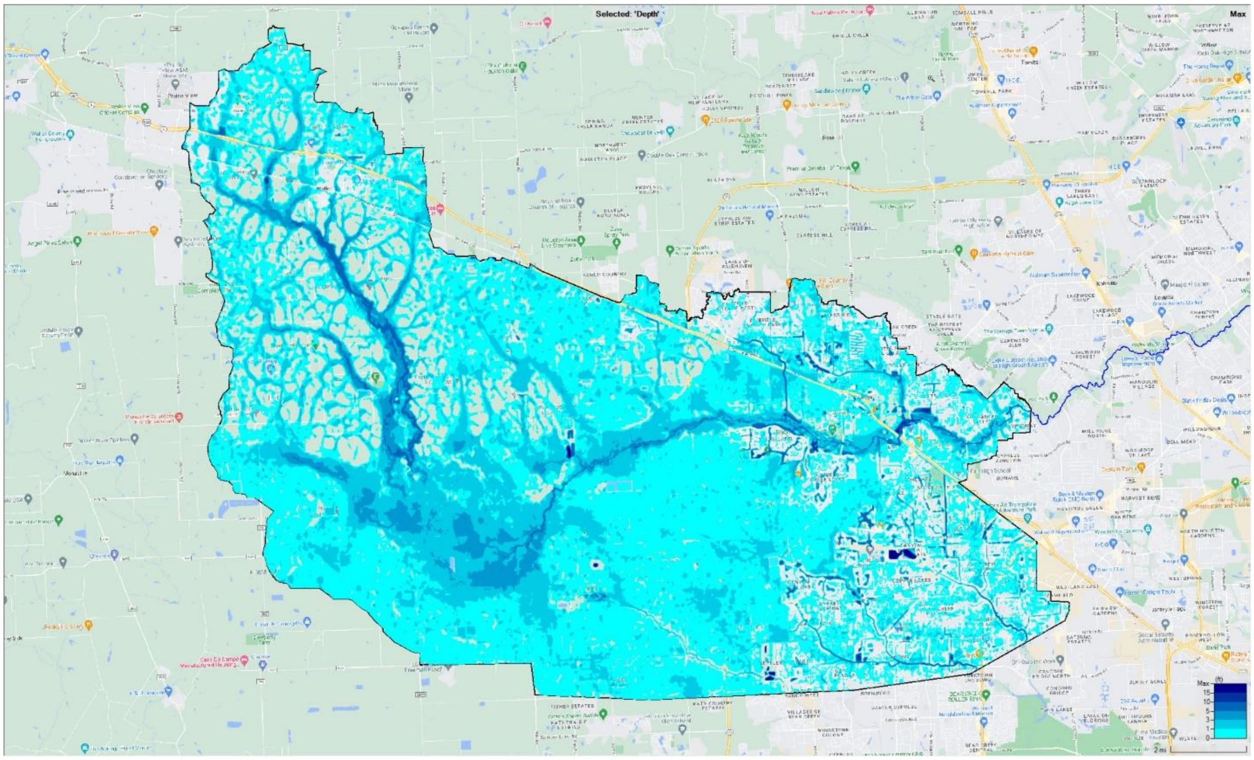


**Figure F-15c. Maximum Modeled Inundation for the 25-year Frequency Storm Event**

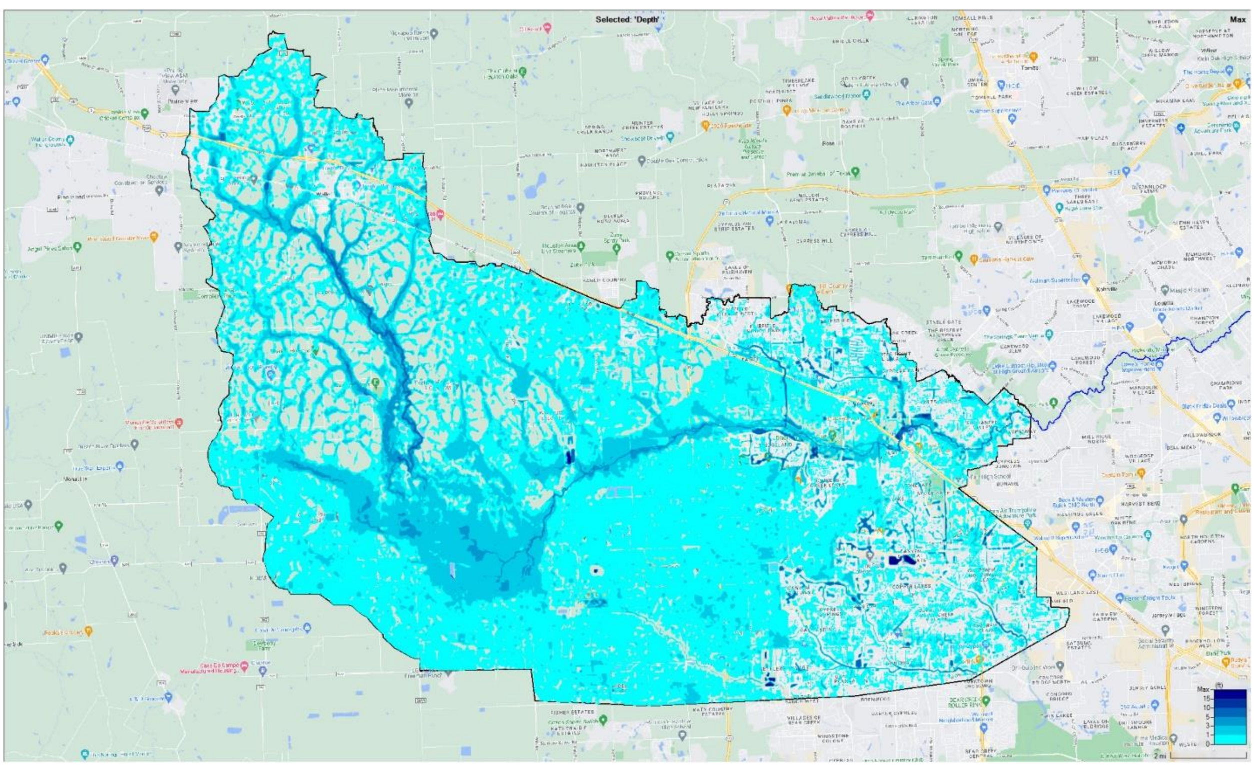


**Figure F-15d. Maximum Modeled Inundation for the 10-year Frequency Storm Event**

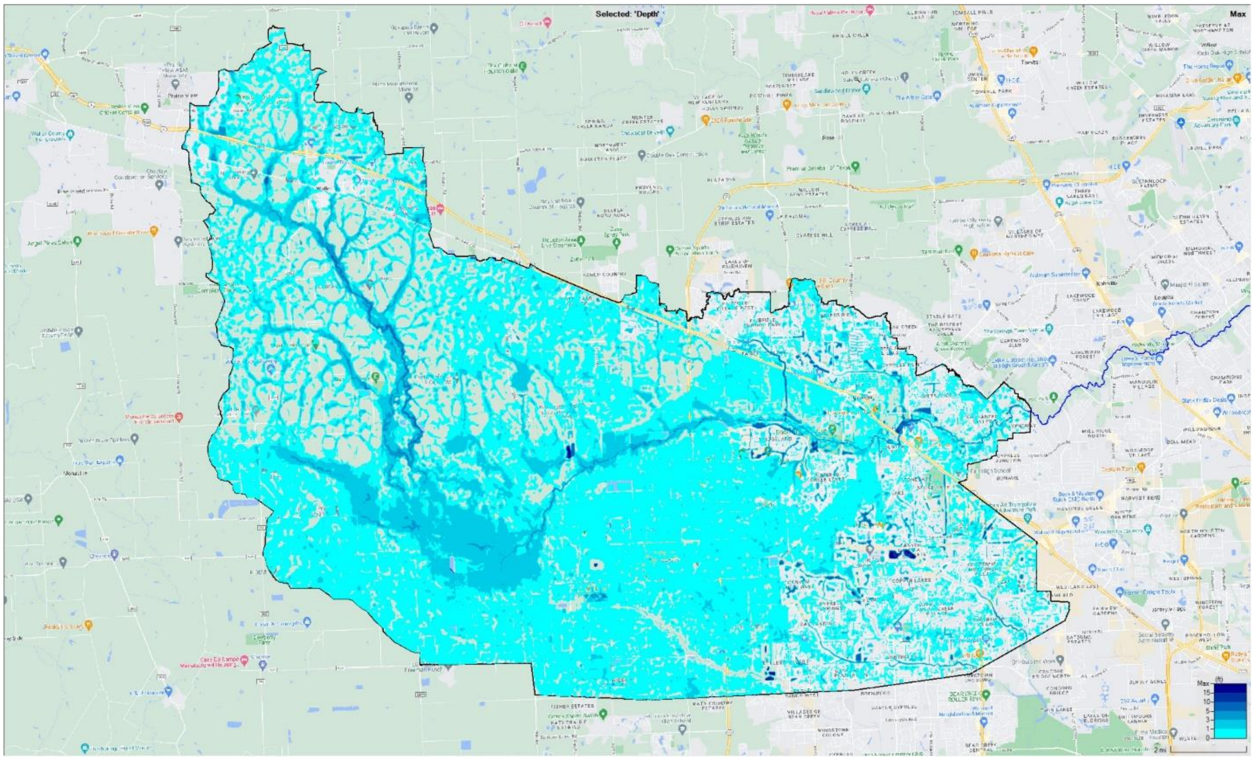


**Figure F-15e. Maximum Modeled Inundation for the 5-year Frequency Storm Event**

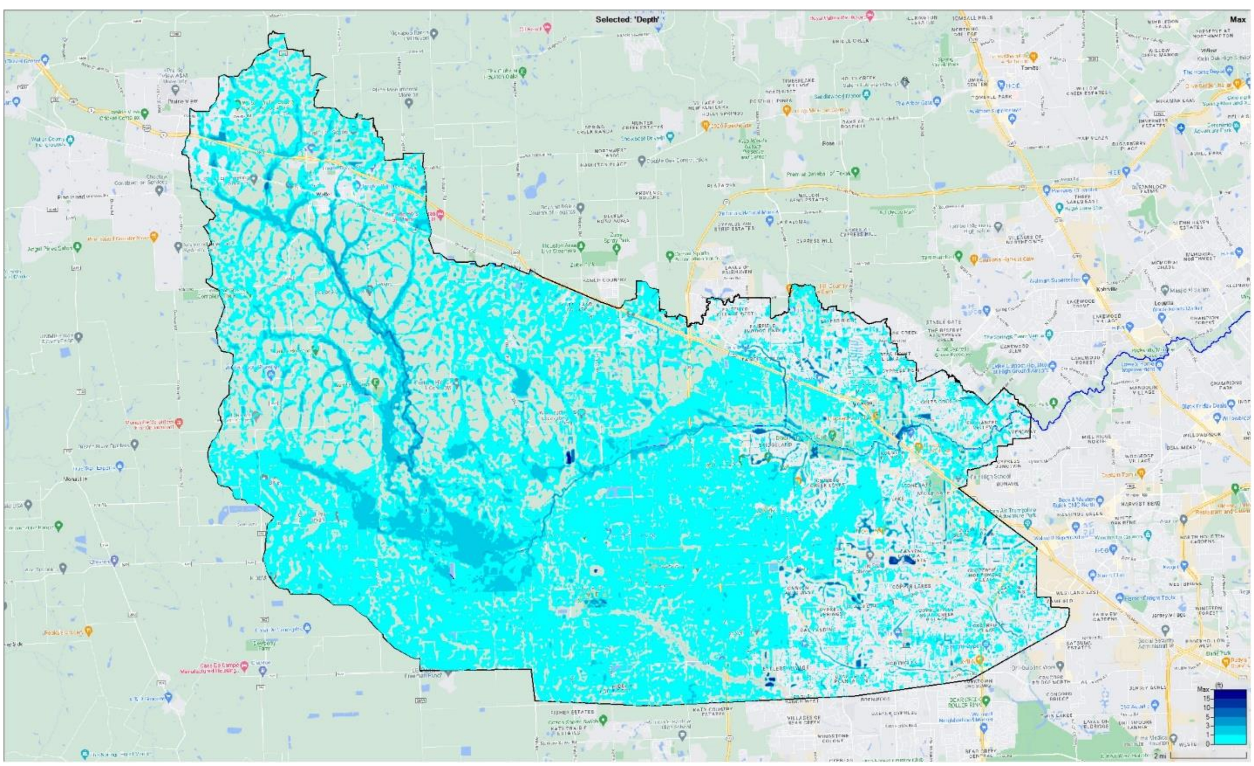


**Figure F-15f. Maximum Modeled Inundation for the 2-year Frequency Storm Event**

This 2D model was then run for the 10- and 100-year storm events with Scenario 1 (S1) in which the existing land cover on the 30,000 acres of CPC lands (including its expansion) was converted to native prairie vegetation. This was done to show the detention benefits of doing such a conversion in the land cover, as presented in **Figures 17a-c.**

Figure 17a shows the flow comparison between the existing land cover condition and the converted condition (S1) at the Cypress Creek overflow area. As can be seen, the peak flows and the volume of the overflows are reduced, and the timing of the peak is delayed.

Figure 17b shows the flow comparison at the Katy Hockley gage, where there is also a reduction in the peak flows and a delay in the timing of the peaks. The same is true at the House Hahl gage as shown in Figure 17c.

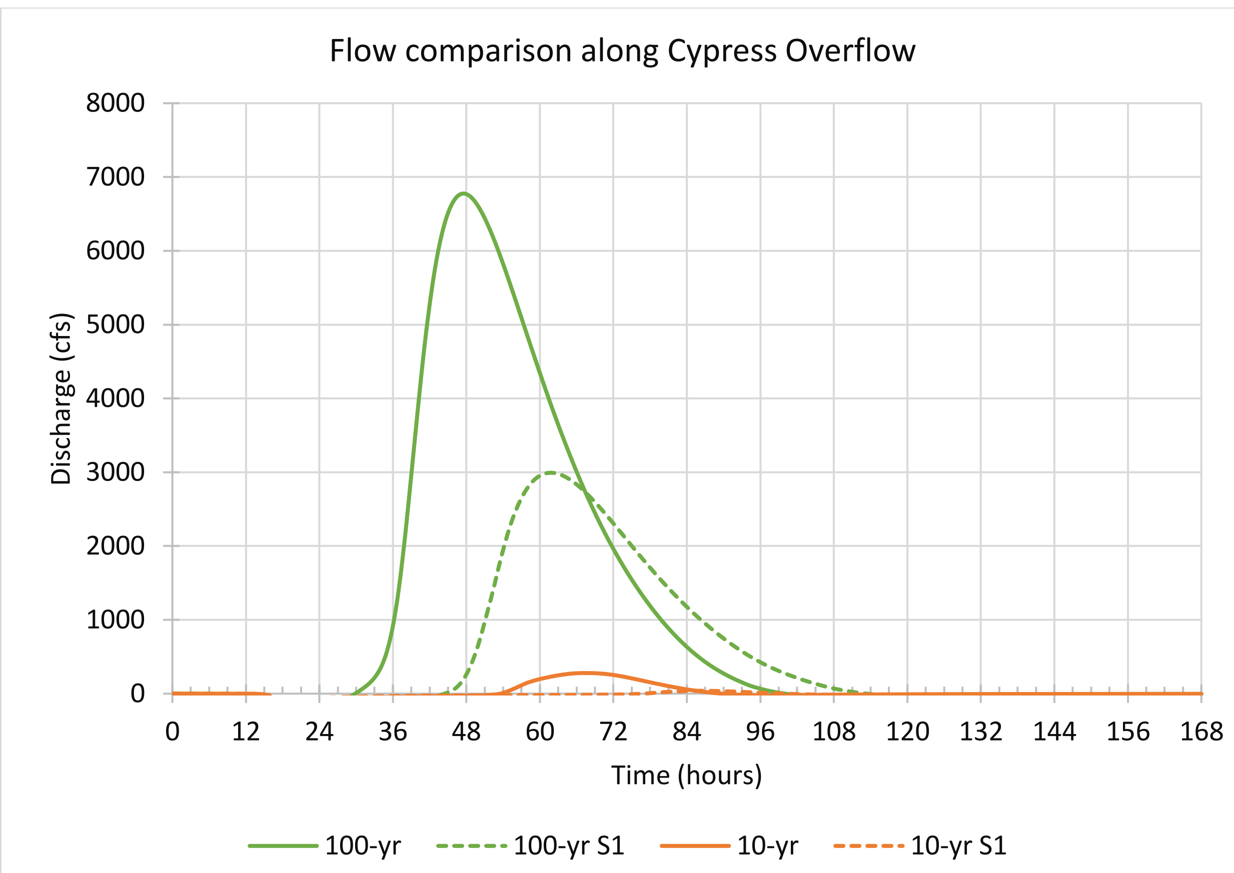



**Figure F-17a. Comparison of Flows Between Existing Conditions and Scenario 1 at Cypress Overflow for 10- and 100-year Storm Events**

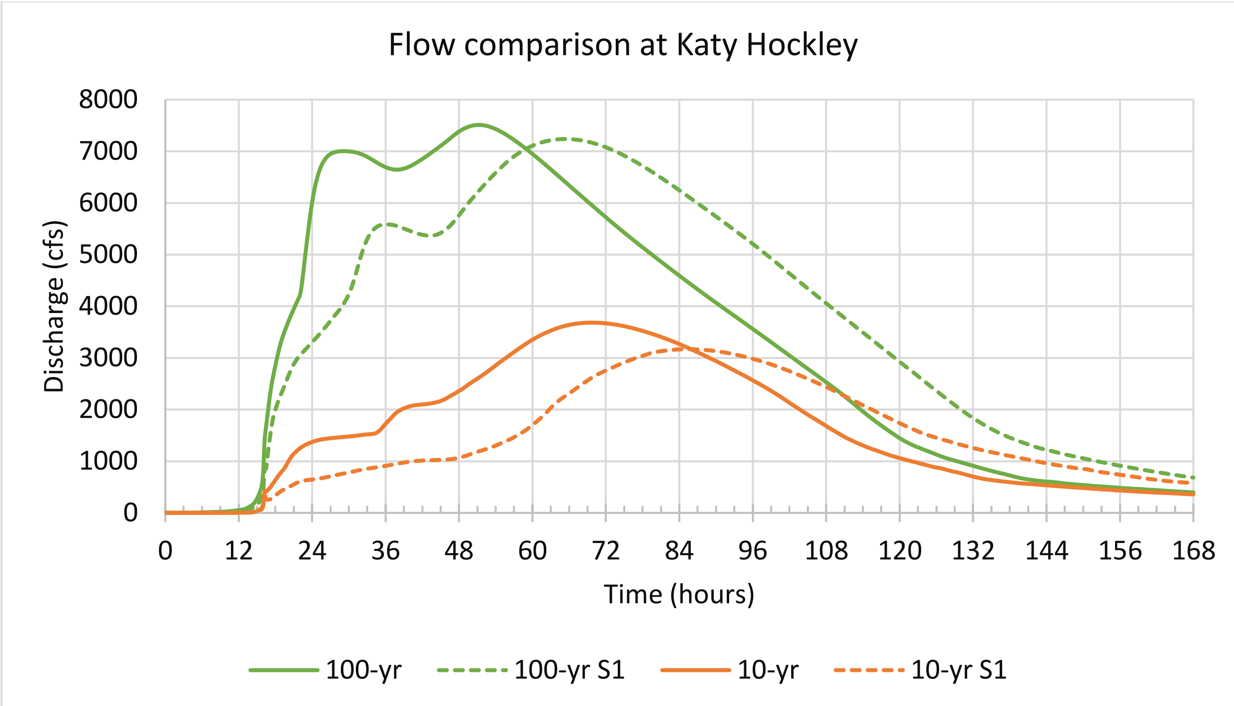



**Figure F-17b. Comparison of Flows Between Existing Conditions and Scenario 1 at Katy Hockley for 10- and 100-year Storm Events**

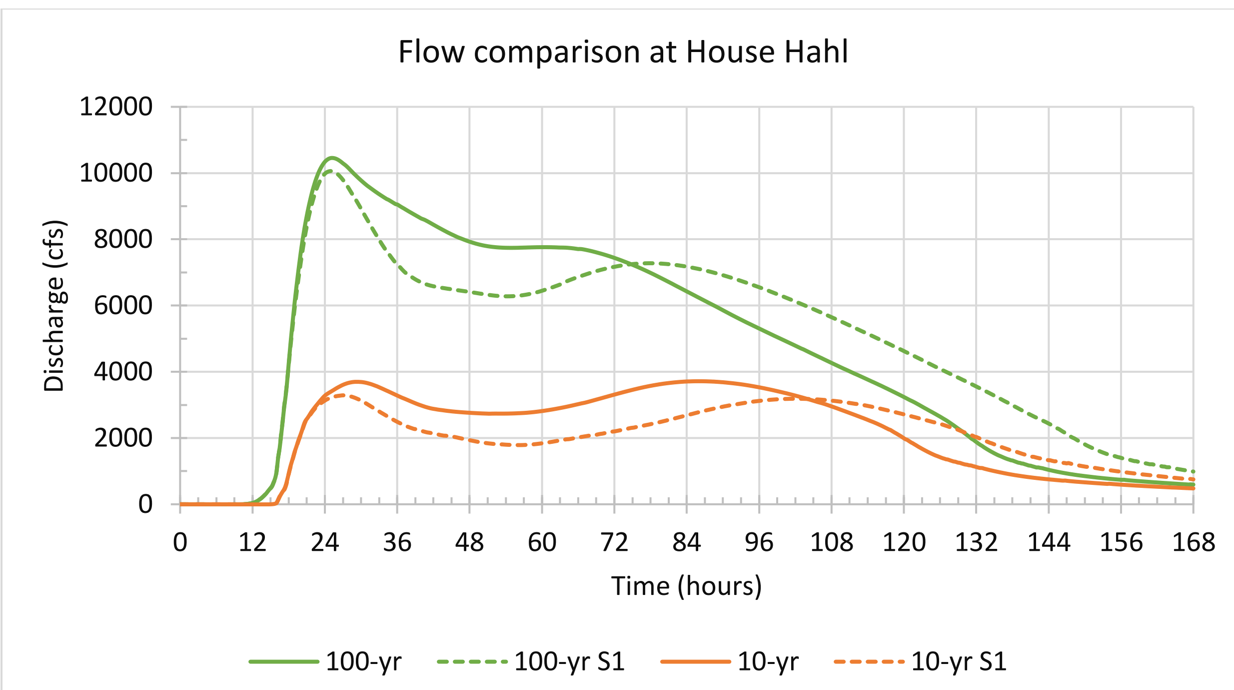



**Figure F-17c. Comparison of Flows Between Existing Conditions and Scenario 1 at House Hahl for 10- and 100-year Storm Events**

# References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